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# Rammed Earth Walls for Farm Buildings

R.L. Patty

L.W. Minium

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JUNE, 1945

# Rammed Earth Walls for Farm Buildings

Agricultural Engineering Department  
AGRICULTURAL EXPERIMENT STATION  
SOUTH DAKOTA STATE COLLEGE  
Brookings, South Dakota



### **Third Edition**

This is the third edition of Experiment Station Bulletin 277. It is slightly revised. Most of the material on protective coverings for rammed earth walls, which was formerly included in this bulletin, has been removed since it is now included in Experiment Station Bulletin 336 entitled "Paints and Plasters for Rammed Earth Walls" published in 1940.

### **Explanation of Cover Cut**

The South Dakota Poultry House Built with Walls of Rammed Earth.

The house was built on the State College Poultry Farm in 1932 and stuccoed in 1934. Both walls and stucco still are standing satisfactorily and without any maintenance or repair cost. The crack in the stucco at the front corner was caused by extending the stucco from the wall to the concrete foundation without leaving a joint. The two have a different coefficient of expansion. It cost \$19.50 to stucco this house. The material cost \$7.50 and the labor \$12.00.



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# Rammed Earth Walls for Farm Buildings

By RALPH L. PATTY and L. W. MINIMUM<sup>1</sup>

Department of Agricultural Engineering  
State College Experiment Station, Brookings, S. D.

## Introduction

Rammed earth walls are made by ramming ordinary moist earth into forms. The walls are rammed in place directly upon the building foundation and in sections. The forms are similar to those used for concrete construction except that they must be much stronger and heavier. The ramming may be done either by hand or by mechanical power. In reading this bulletin it will be very helpful if the table of contents is consulted for the subjects.

The purpose of this experimental study of "pise'" construction was to secure definite and reliable information with which we could answer the many inquiries concerning it that were coming to the South Dakota Agricultural Experiment Station. The wide range of soil types over the state of South Dakota made it impossible to make reliable recommendations as to its use for this construction without a careful and detailed study of South Dakota soils, and of soils in general, for this purpose. This is a progress report.

Earth construction for building walls is not a new idea. In fact, it is ages old. Buildings were built of earth centuries ago in Europe, and while the methods used differed widely, some of this construction was of rammed earth. It is claimed that it was used by the early Romans and was introduced into France by them. The following paragraph is taken from Farmers' Bulletin No. 1500 by M. C. Betts and T. A. H. Miller.

"Pise' de terre (pronounced pee-zay duh taire), which means rammed earth in French, is an ancient type of construction. The writings of Pliny state that watch towers of this material constructed by Hannibal

were in use 250 years after completion. It was introduced into France by the Romans and later adopted in England."

Buildings of these walls have been used in the United States also to a limited extent. According to California Experiment Station Bulletin No. 472 by J. D. Long, some of the settlers of our early colonies built of this material. One two-story rammed earth residence now in use in Washington, D. C., is said to have been erected in 1773, and a modern residence was built of this material in Washington within the past few years by Dr. H. B. Humphrey.

**Other Types of Earth Walls Compared.**  
There are several types of earth wall construction besides the pise' or rammed earth with which this study deals. Adobe walls, as the term is generally understood and defined, are made of a wet plastic mixture of earth or mud. Adobe walls should not be confused with rammed earth as they are quite different, the adobe being mud-like while the pise' walls are rammed moist earth. The most common adobe construction is with blocks. The mud is pressed and molded into large bricks usually 18 inches long by 12 inches wide by 4 inches thick. These are often reinforced with straw, and after they are molded they are set out to dry. When they are properly cured they are laid into a wall in the same way as concrete blocks. Adobe or mud walls are also made

<sup>1</sup>Mr. Minimum has been with the Soil Conservation Service since 1934. The authors particularly wish to acknowledge the cooperation of Professor H. M. Crothers, Dean of Engineering, and of Associate Professor Leo Puhr of the Agronomy Department, Professor W. E. Poley and Prof. W. C. Tully of the Poultry Husbandry Department, and Dr. K. W. Franke of the Chemistry Experiment Station, South Dakota State College.

by packing the wet mud into forms, making a monolithic wall. In most of these walls straw or other binder material has been generally used. There are other variations in the use of earth for wall construction that are of less importance and perhaps less practical. In the South Western states the adobe brick are used extensively. Mexican laborers are generally more or less experienced in making these brick and the work can be done when farm work is slack. The authors believe the rammed earth wall may be better adapted to the North Central section of the United States because of inexperience in making adobe brick, and because of a great deal of experience in building of concrete and the use of forms in making monolithic walls. The monolithic wall is also entirely resistant to the infiltration of cold air in winter. It is also stronger and more stable. The rammed earth wall is a "once over, all over" method. It saves two or three handlings of the soil and also saves the mortar for laying the bricks. In a warm climate of even temperature, mud is fairly satisfactory for the mortar used to lay the bricks, but for more northern climates where loosening of the mortar joints would result in a cold wall, the monolithic or one-piece wall should be preferable. The heavy forms used for rammed earth construction are not built all the way around the foundation of the building as for pouring concrete. One or two sections of form only are required. The wall is rammed a section at a time, and after one section is rammed the form is then moved ahead and another section is rammed.

The soil used for rammed earth walls is not wet and in no way approaches mud. Generally the soil that is excavated for the basement of a house will be too moist for making the best walls. Soil that will make a mud ball is too wet. It should have only enough moisture in it to mold nicely when it is pressed in the hand. Clean soil of this moisture content is easy to handle and makes a wall that will not check badly, one that is smooth and resistant to shock, a good insulator and a surface that does not bake.

A recent development in earth wall materials has been made by a leading distrib-

utor of asphalt emulsion oil used for stabilizing soils. It is called "Bitudobe" and is a stabilized adobe brick. Asphalt emulsion is used for the stabilizer and is mixed with the puddled soil or mud as the bricks are made. The bricks are generally made smaller than the common adobies, being about 12 by 12 by 4 inches. These bricks are moisture resistant and much superior to the common adobies. The Station has worked with these bricks to quite an extent but has published nothing on it. Their use is more practical when they can be made at a factory, as they were found very difficult to make without special mechanical equipment.

Two other types of earth walls were used extensively in Europe in early days. They were called "chalk" and "cob" walls. They were very thick, solid walls made of mud and straw. They were tedious to build because each layer of mud placed on the wall had to dry out before the next layer could be laid.

**Insulating and Air Conditioning Quality of Rammed Earth Walls.** One very important reason for this experimental study is the need for insulated walls for housing livestock and poultry in climates subject to cold weather in the winter season. Moisture and frost accumulate on the inside surface of cold side walls in such a climate. The greatest damage from this frost accumulation comes when the weather moderates. The thawing of the frost from the walls makes the building damp and creates a condition that is unhealthful for livestock and particularly bad for poultry. Rammed earth walls are excellent insulating material and have proved very satisfactory in the control of moisture and frost. A poultry house was built with rammed earth walls and straw loft on the College Poultry Farm<sup>2</sup> for the purpose of comparing frost deposit and inside temperatures with several other houses.

During the first part of the 1932 winter season the weather was abnormally cold and the temperature dropped to 18 degrees below zero. A thorough inspection of the inside walls during this period revealed no

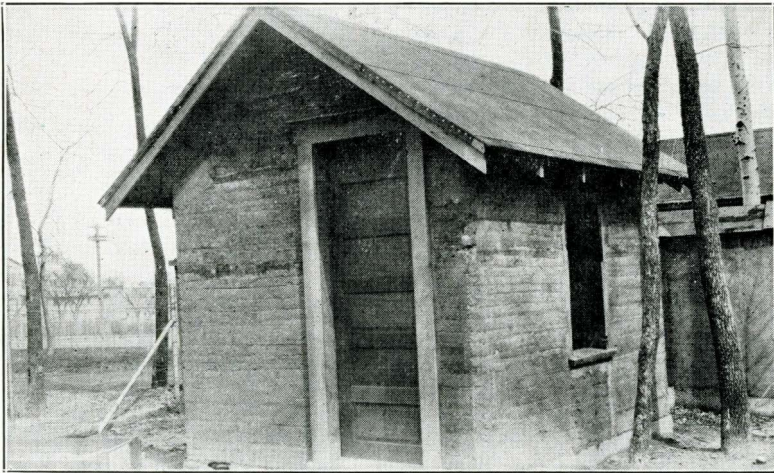
<sup>2</sup>See page 48.



trace of frost on the inside walls of the rammed earth house, while in the other houses the frost deposit varied from light to heavy. Later in the season the temperature dropped to 30 degrees below zero and the frost deposit on the rammed earth walls was almost as heavy as on the walls of other houses of frame construction with average insulation. All of these houses had straw lofts except one, and in this house the frost condition was more than twice as bad as in the rammed earth house. The frost did not make the inside of the rammed earth house damp as it did the others. The wall absorbed the moisture very readily as the frost melted and when the air later became dry this moisture was returned to the air. The rammed earth wall was only 12 inches thick.

It was a desire on the part of the Experiment Station to find an inexpensive and satisfactory wall for the farm poultry house that made this study of economic importance. A cooperative study of this poultry house is being carried on at the present time by the Agricultural Engineering department and the Poultry Husbandry department.

Rammed earth construction lends itself well to construction of simple buildings with comparatively low sidewalls and few wall openings. A building such as average-sized farm poultry houses can be built above the foundation in 10 days to two weeks' time by an experienced crew of three men. If the labor must all be hired there will be little, if any, saving in the cost of the walls over those built from lumber or building tile. The advantage of rammed earth construction must be in utilizing labor for which little or no cash need be paid and in securing an exceedingly warm and dry sidewall for the poultry house. For more elaborate buildings of more than one story the work is more tedious, forms and frames for openings require more time, and if the labor is hired the cost is apt to be fully as great if not greater for rammed earth construction than for other materials. However, this study has verified former claims made by investigators and enthusiasts for rammed earth construction that most excellent homes and buildings can be built of earth if desired. Although under normal conditions the cost of elaborate buildings of rammed earth may



**FIG. 1. A SMALL RAMMED EARTH BUILDING USED FOR EXPERIMENTAL PURPOSES**

One writer suggests that it would be a good idea for one who is planning to build rammed earth walls to build a small building first in order to become accustomed to the soil and to the handling of the forms. The authors do not believe this is necessary, but a small building such as a smokehouse or garage would be a good one to build if it is desired to follow this suggestion.

be as high as ordinary uninsulated frame houses, the walls, if kept well stuccoed, should last indefinitely and be especially valuable for modern air conditioning.<sup>3</sup>

One author<sup>4</sup> recommends that before starting on an elaborate building of rammed earth it would be well first to build a small simple structure and thereby become familiar with the use of the forms and the characteristics of the soil. Such a building might be a small smokehouse or a farm poultry house.

Mechanical rammers may be used in the constructing of rammed earth walls. Their use will cut down the labor hours for this work but the cost of a complete compressed air outfit for ramming will cost several hun-

dred dollars at the present price. The California Experiment Station<sup>4</sup> reports that with the mechanical rammer a construction speed of 7 cubic feet per man hour was secured. With hand ramming, a speed of 2 cubic feet per man hour would be about as much as could be expected of an experienced crew of men. In building the walls of the poultry house at the South Dakota Experiment Station the speed averaged one and one-half cubic feet per man hour. Student labor was used entirely for this work, however, and the work was not only done intermittently but new men had to be broken in.

<sup>3</sup>Coffin-Humphrey, "Lower Cost Buildings."

<sup>4</sup>J. D. Long—California Experiment Station Bulletin No. 472.

## Methods Used for Testing Soil and Walls

The purpose of these studies was to learn the structural characteristics of soils favorable to rammed earth construction, to determine the optimum clay and sand ratio and the optimum moisture content for both strength and weathering resistance in rammed earth walls. Further studies were made on protective coverings, on the effect of adding fiber to the soil, on rammers and the proper ramming of soil into the forms, on reinforcing for wall openings and corners, and on the best practices in building walls of this material. Finally, the study of the cost and economy of rammed earth walls and their relative insulating value in the control of frost deposit when used for housing livestock, was made.

The strength tests in compression were made to determine the relative value of certain soil characteristics or building practices, and not because its strength for farm building walls was questioned. Walls made from soils showing the lowest strength are amply strong to carry the compression load in walls. Although there is a tendency for planes of cleavage to develop between the layers of earth as they are rammed in test blocks and beams, they did not prove to be a factor of importance in walls. Various at-

tempts have been made to overcome this difficulty in the test pieces and some results have shown improvement but nothing entirely satisfactory. Work is still being done on this problem. Samples of soils from all parts of South Dakota were analyzed and tested both for strength and for resistance to weathering. These soils were taken from 18 counties of the state and covered the extreme territories.<sup>5</sup>

**Test Blocks and Beams.** All early test blocks were cubical in shape and were 9 by 9 by approximately 9 inches. They were about as heavy as can be conveniently handled, weighing from 45 to 60 pounds when first made, depending upon the amount of sand in the soil. They were rammed in forms and with hand rammers. They were handled on board trays 12 inches square.<sup>6</sup>

The test beams were made for the reinforcing study and were 36 by 12 by approximately 7¾ inches in depth. They weighed from 250 to 260 pounds and were handled on slat trays approximately 10 inches by 48 inches.

<sup>5</sup>See *Resistance of Rammed Earth Walls to Weathering*, p. 20.

<sup>6</sup>Cylindrical test blocks were used later in the study.

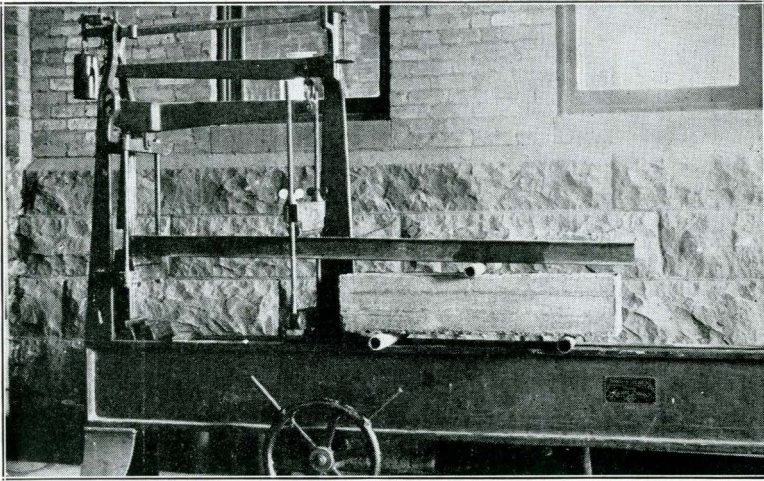


FIG. 2. TESTING RAMMED EARTH BEAMS USED IN THE REINFORCING STUDY

The beams were 36 inches long, 12 inches wide and  $7\frac{3}{4}$  inches high. The reinforcing materials were placed one and one-half inches from the bottom of the beam. The span used in the test was 24 inches and force was applied at the top, midway between the two contact points. The Olsen testing machine was used.

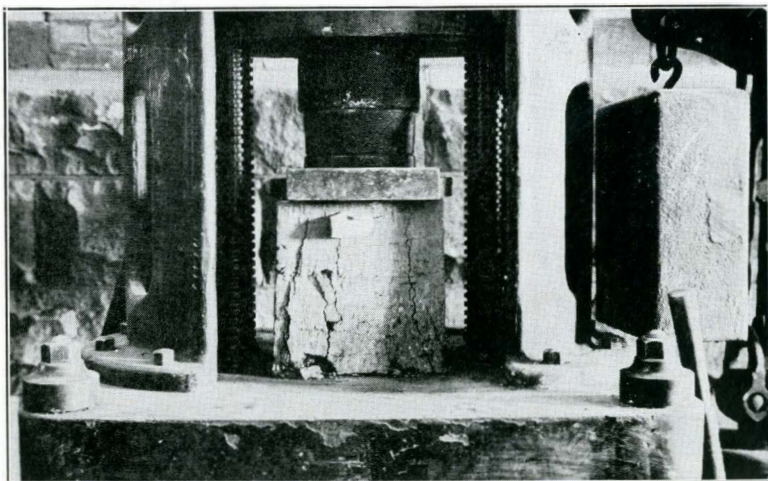
**Testing the Soil for Moisture.** The moisture tests of soils were made in duplicate. Measures of the soil were taken from six different points in the pile and placed in a small sample pile which was then mixed and quartered. From this soil, duplicate samples of 400 to 500 grams each were placed in soil pans. These were weighed and placed in an electric dispatch oven, where they dried out to constant weight at a temperature of approximately 220 degrees F. The samples were then reweighed and the loss of moisture figured. The per cent of moisture was then determined by dividing the loss of moisture by the net weight of the wet sample of soil. The average of the duplicate figures was used for the true moisture percentage.

**Testing the Blocks for Strength in Compression.** All test blocks that were tested for strength in compression were stored in the research laboratory in a temperature around 70 degrees F. until the moisture content was reduced to almost a constant figure. This moisture content averaged below three per cent at the time they were broken. In order to determine the moisture contained

in the blocks at any time, the blocks were weighed immediately after they were made and when the moisture content of the soil was known. By reweighing a block at a later date the moisture content could be figured from the loss in the weight of the block. This was done in the following manner: The weight of the new block multiplied by the moisture content of the soil from which it was made, in per cent, gave the weight of water in the block in pounds.

After the block had dried out it was reweighed and the loss of weight in pounds (which was necessarily the weight of the moisture lost) was subtracted from the pounds of water originally in the block. This gave the weight of the moisture, in pounds, that was left in the block, and dividing this figure by the weight of the dry block gave the moisture content of the dry block in per cent. The blocks were handled at all times on a small board tray 12 inches square and of known weight, so that no loss of weight could result in handling. The blocks were made in the form of cubes 9x9x9 inches. It was not always possible to get the depth of the blocks exactly nine





**FIG. 3. TESTING THE RAMMED EARTH BLOCKS FOR COMPRESSIVE STRENGTH**

The blocks were crushed in a Riehle testing machine when their strength in compression was desired. This block shows a typical failure, indicating a sound block or one without any special flaw or weakness. It failed under a load (ultimate load) of 36,000 pounds or 18 tons, which is about an average strength for South Dakota soils. The dimensions of the block are 9x9x9 inches. Four hundred of these test pieces have been broken so far in the study.

inches and when this variation was sufficiently great, correction was made for it. The blocks were crushed in a Riehle testing machine.<sup>7</sup>

Since the bottoms of the blocks were perfectly square and level, they were seated upon a one-fourth inch fiber pad for the test. A sand cushion leveling the top of the block and covered with a second fiber pad was used on the top of the block. The strength figures are surprisingly uniform for these test pieces of such material. Similar test blocks of a series seldom varied more than three or four per cent and an average of three or four blocks has usually proved a reliable and satisfactory figure. The manner of testing the test beams is described under the paragraph on "Reinforcing in Rammed Earth Construction," and a picture of the test is shown in Fig. 2.

**Soils Used for Standard in Tests.** Three standard soils were used for making test pieces when a standard base soil was needed for comparing the effect of certain conditions or practices. They were designated as

Experimental Soil No. 1, Experimental Soil No. 2, and Experimental Soil No. 3. Experimental Soil No. 1 was a black clay soil obtained in a valley one-half mile north of the Experiment Station. It is composed of 89.6 per cent silt and clay and only 10.4 per cent of sand, most of which is fine. Experimental Soil No. 2 was a yellow clay loam soil found in the subsoil under all of the higher ground upon which the college campus is located. It averages only 62.5 per cent clay and silt and contains 37.5 per cent of total sand ranging in size from particles that are just retained upon a very fine screen of 200 mesh to the lineal inch, up to one inch in size. Experimental Soil No. 3 was a darker yellow sandy clay soil found in a certain local area near the campanile on the State College campus. This soil is very high in total sand and gravel content, containing only 25.2 per cent of clay and silt with a total sand or aggregate content of 74.8 per cent. The aggregate is very well graduated in size, varying all the way from the 200-mesh size up to two inches. This soil made one of the five best walls

<sup>7</sup>See Fig. 3.

in the yard; all have stood satisfactorily as bare walls for 15 years and were built from soil without any addition of sand.

**Mechanical Analysis of Soil Samples.** In analyzing the soils, at first no attempt was made to separate or study the silt and clay materials. The analyses were made in the following manner: Duplicate samples of approximately 500 gms. were thoroughly dried in the electric dispatch oven until reduced to constant weight. They were then weighed and passed through the following sized screens in order: three-fourths inch, one-half inch, and one-fourth inch. The sample was then screened through the one-eighth inch, the 100-mesh (100 mesh to the lineal inch), and the 200-mesh screens under a stream of water. The sand retained on these screens was then dried and each size was carefully weighed. For simplicity the total aggregate,

from the finest particles that were retained on the 200-mesh screen up to the largest pebbles, will often be referred to in the tables and in this bulletin as "sand." All soil particles that passed through the 200-mesh screen were considered silt and clay.

NOTE: Since 1934 a different method of analyzing soils has been used. It is known as the hydrometer method of analysis, and with this method the silt is separated from the clay so that the total sand, total clay, and total silt in a soil are determined. The soil sample must be taken very carefully so that it will be exactly representative of the soil that will be used in the walls. Prospective builders may obtain instructions for securing and sending in samples to the laboratory for analysis by addressing the Agricultural Experiment Station, State College, Brookings, South Dakota.

Table 1. Mechanical Analysis of Three Base Soils Used in Experimental Blocks and Beams  
Analysis with 200-Mesh Sieve

Soil	Color	Number of samples averaged	Total silt and clay per cent	Sand			Gravel		Total aggregate per cent
				200 to 100 mesh screen	100 to 1/8 in. mesh screen	1/4 in. to 1/8 in. mesh screen	1/2 in. to 1/4 in. mesh screen	1/2 in. screen and above	
Experimental Soil No. 1	Black	4	89.641	4.514	5.76	.085			10.36
Experimental Soil No. 2	L. Yellow	4	62.44	8.799	25.354	1.918	1.662	.826	37.56
Experimental Soil No. 3	D. Yellow	4	25.18	4.690	41.870	9.390	7.200	11.670	74.82

### Relation of Sand Content, Moisture, and Shrinkage in Soils For Rammed Earth Work

The first study made was for the purpose of finding out the effect of sand content and moisture, in the soil used, upon the rammed earth wall. Thirty-nine test blocks were made for this study with the idea of observing them and later of testing them for compressive strength. Five different amounts of sand were used in this series of blocks and the moisture was varied from high to low in three graduated amounts within the bonding range. The blocks were closely observed as they dried out and the shrinkage was measured. After the blocks had dried to constant weight they were tested for com-

pressive strength in a Riehle testing machine and the results are given in Table 2.

**Moisture and Sand.** This study disclosed several relationships between the amount of moisture in the soil and the properties of the rammed earth. It was found that the optimum moisture for ramming varied in inverse proportion to the amount of sand in soil, as the sand in the soil was increased the required moisture decreased. This is due to the fact that soil that is made up of small particles (silt and clay) has a much greater surface area for moisture than soil containing coarser particles of sand and gravel with

the silt and clay. A sandy soil containing only seven or eight per cent moisture would be satisfactory while a clay soil with this per cent of moisture would be altogether too dry to ram. It would require 16 to 18 per cent of moisture to bring this soil up to the optimum moisture for ramming. Bank-run sand and gravel alone will be quite wet when containing only three or four per cent of moisture.

**Moisture and Strength.** The amount of moisture in the soil when it is rammed has a decided effect upon the strength of rammed earth in compression. When too dry, all soils seem to lose strength markedly, and in most cases soils that are too wet show a low strength. This is particularly evident with sandier soils and it is probable that this may be due to the larger amount of space left in the block after the moisture has evaporated. Such a block seems much less dense and the present status of the study, purely from the strength standpoint, indicates that in rammed earth construction density may be as important a factor for strength as it is in concrete.

**Sand and Strength.** The results have not as yet shown definitely that the strength of

rammed earth varies in inverse proportion to the amount of sand in the soil, but there is no doubt of this proportion for higher amounts of sand. It is highly probable that, in general, soils containing 30 per cent or more of sand decrease in strength in inverse ratio and possibly this ratio might carry all the way through if the weakening effects of cracking and checking in the blocks containing little sand could be avoided. However, strength is secondary in importance. All walls will have ample strength. Sand in the soil makes them durable. This is of first importance.

**Moisture and Shrinkage.** The study leaves no doubt about the relationship of moisture and shrinkage. Regardless of the soil and its characteristics, the amount of shrinkage varies in direct ratio with the amount of moisture in the soil at the time it was rammed, i.e., provided the moisture is sufficient to bond the soil particles well. This fact is also shown in Table 2. Although the shrinkage may not be very great in the sandier soil, it will increase with the increased moisture. With the less sandy soils shrinkage is not only a very serious and undesirable factor in rammed earth construction but may be a

Table 2. Relation of Moisture, Strength and Shrinkage in Rammed Earth Test Blocks\*

Per cent moisture content in soil	Sand 0 to 5 per cent		Sand 10 to 20 per cent		Sand 25 to 35 per cent		Sand 42 to 53 per cent		Sand 55 and above	
	Per cent shrinkage	Strength compression lbs. per sq. in.	Per cent shrinkage	Strength compression lbs. per sq. in.	Per cent shrinkage	Strength compression lbs. per sq. in.	Per cent shrinkage	Strength compression lbs. per sq. in.	Per cent shrinkage	Strength compression lbs. per sq. in.
6									.14	147.7
7							.18	226.1	—	191.5
8								141.4	.00	198.5
9					.80	464.1	.91	404.1	.68	292.3
10			1.33	374.3	.66	626.0	.662	609.5	.00	246.0
11	.42	273.	1.72	439.0	.66	531.6	.50	509.0	.15	205.8
12	.40	877.5†	1.85	605.	1.35	523.5	1.19	381.0	.33	441.0†
13	1.66	400.	1.51	493.	1.30	353.0				
14	2.43	576.5			.86	352.5				
15	2.8	385.								
16			2.01	522.	2.04	511.0†				
17			3.16	344.5						
18	2.23	692.0†	1.00	270.						

\*Later findings show that some of the variations in strength in this table were due to a difference in the age of the test piece when broken.

†Figures that fall out of line for the strength curve.

NOTE: As the sand content increases the shrinkage decreases. As the sand content increases above 35 per cent the strength decreases. As the moisture increases the shrinkage increases.



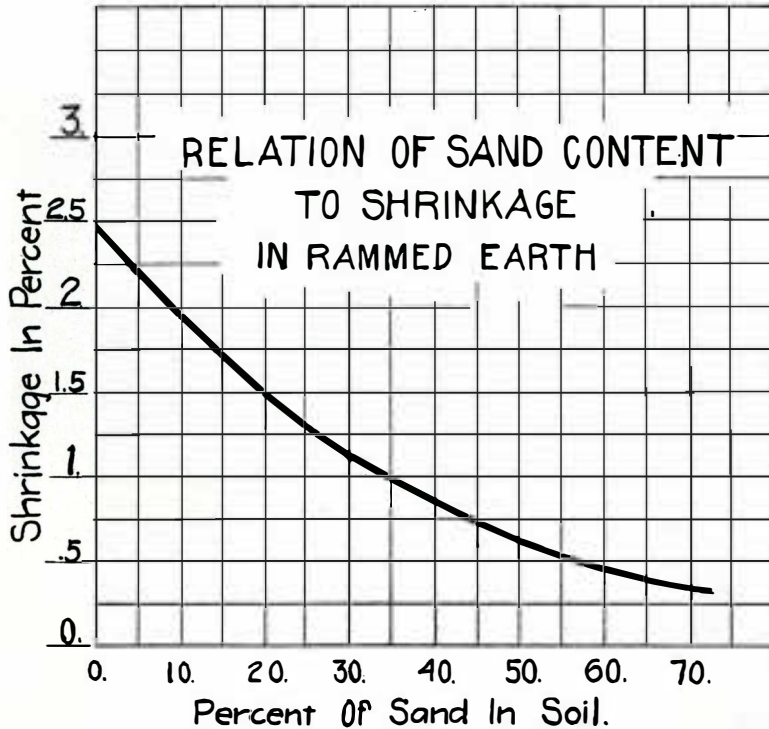


FIG. 4. AS THE SAND INCREASES IN THE SOIL USED FOR RAMMED EARTH THE SHRINKAGE IN THE WALL DECREASES

This curve is developed from the average shrinkage of test pieces used in compiling Table 2.

limiting factor. In these soils a comparatively large amount of moisture is needed to make them wet enough to bond and this means a high shrinkage and large shrinkage cracks and checks.<sup>8</sup> These checks appear to reduce the resistance of the soil to weathering, causing them to crumble away when the surface is exposed to the weather. This may not be in direct proportion but apparently it generally is.

**Sand and Shrinkage.** Sand in the soil reduces shrinkage of rammed earth in direct proportion by reducing the amount of moisture that is required in the soil at the time it is rammed. Soils containing 50 per cent or more of sand do not shrink enough to cause cracking or checking of the wall to any ex-

tent. In this connection it is interesting to note that in a long wall there will be some shrinkage, however, and that the amount of shrinkage that will be expected can be figured. In order to figure it, it is first necessary to determine the shrinkage coefficient of a certain soil by testing. For instance, if it is found that a test block of a certain soil shrinks .5 per cent, then for every 100 inches in the length of the wall there will be a shrinkage of one-half inch. This may be largely taken up or absorbed in many hair-like cracks or there may be a larger one or two, or the joint between the sections of the wall as they were rammed may pull apart slightly to take up this shrinkage. The shrinkage of the blocks has been difficult to measure as accurately as desired.

<sup>8</sup>See Fig. 5.

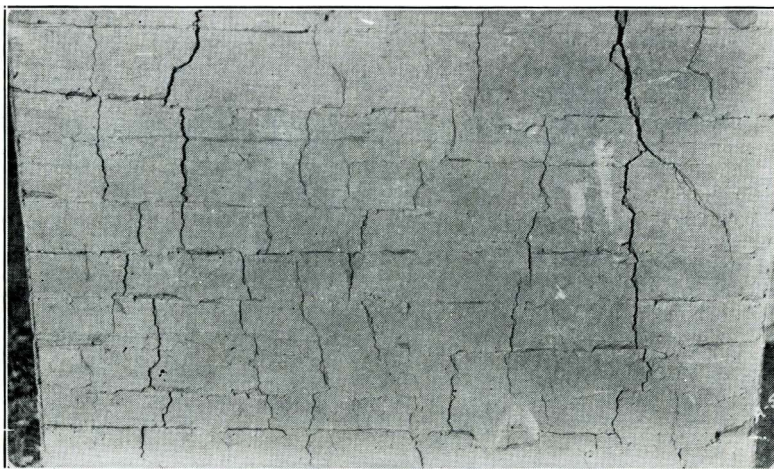


FIG. 5. A PISE' WALL FROM SOIL IN WHICH THERE WAS TOO MUCH CLAY

The checks and cracks shown in this wall section were caused by shrinkage forces and are typical of heavy clay soils in which there is very little sand. This soil contained only 11 per cent of sand by weight, and the 89 per cent was silt and clay. This soil is unfit to use because of high shrinkage. The addition of sand will not make a favorable soil from one originally containing 30 per cent or more of pure clay.

For practical purposes the results of the study of this relationship for sand, moisture, and shrinkage show that the optimum moisture should be used for best strength and weathering. Although this optimum moisture varies with the amount of sand in the soil, it is easy to determine it by practical tests described in a following paragraph, and with a little experience a mere handling of the soil is sufficient. Sand in the soil reduces the compressive strength of the soil somewhat, but it is very valuable in reducing

shrinkage and in increasing the resistance to weathering. In Table 2, p. 12, the results that are shown not only include the 39 blocks made especially for this study, but include some additional blocks that are of widely different character, thus adding considerable value to the results shown. Practically every strength figure and the corresponding shrinkage figure for a certain moisture and within the range of sand, are averages of several different blocks.

### The Unit Weight of Soils in Rammed Earth

By unit weight is meant the weight of the soil per cubic foot, and in this study it was usually figured for all test pieces after they were thoroughly dried out. However, the figures shown for unit weight in the next table are for test pieces that were newly made and contained all of the original moisture. It is interesting to note the relationship

of unit weight and the sand content in the soil. The three base soils used in all our experimental work were chosen because they represented three widely different soils. In total sand content they vary almost in a direct proportion and their unit weight varies accordingly. The figures shown in Table 3 are averaged from 12 blocks of each soil.

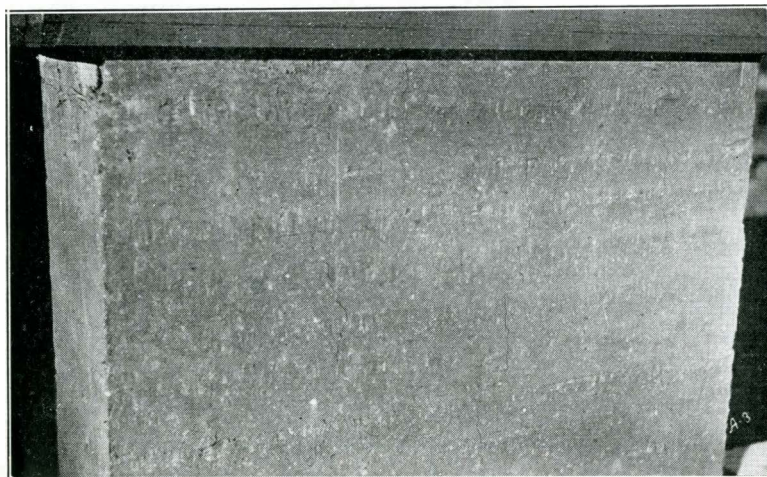


FIG. 6. AN EXCELLENT SOIL FOR RAMMED EARTH WALLS

This wall was made from soil that is almost perfect for rammed earth construction. It is made from Experimental Soil No. 3\* and has stood for nearly fifteen years. This is the south side of the wall, however, and the north side is somewhat roughened from driving rains from the north. This soil contained 74.8 per cent of sand by weight, and the shrinkage for it was almost negligible.

\*See Table 1.

Table 3. The Relation of Sand Content to Unit Weight

Soil	Experimental Soil No. 1 sand content 10.36%	Experimental Soil No. 2 sand content 37.56%	Experimental Soil No. 3 sand content 74.82%
Unit Weight	lb. per cu. ft. 119.4	lb. per cu. ft. 128.38	lb. per cu. ft. 138.87

### Optimum Moisture in Soil for Weather Resistance

One or two experiences in the study suggested that a higher moisture content in the soil than is needed for maximum strength might be desirable for resisting weather. This fact is quite satisfactorily disproved by the following trial. A composite sample of an average soil containing 35.7 per cent total sand was selected and used for making four rammed earth walls. These walls were built exactly alike except for moisture content. They were given the same location in the yard and were made by the same workmen, care being used to ram the same. The first wall was rammed very dry, having only 6.59 per cent moisture in the soil. The second wall was rammed with 9.10 per cent moisture, which is the optimum moisture in this soil for strength in compression. The third

wall was slightly too wet, having 11.58 per cent moisture. The fourth wall was made very wet—in fact, just as wet as it was possible to ram it. The moisture content was 14.01 per cent.

The average soil was used in these walls because they would show the effects of weathering more quickly. Like all weathering walls, the surface was unprotected.

Four years after the walls were built the results were shown very definitely in these walls. The first wall made from the too-dry soil was very definitely the poorest wall. The second wall, having the optimum moisture content, was just slightly better than the third wall. The fourth wall, which was rammed extremely wet, was definitely poor-



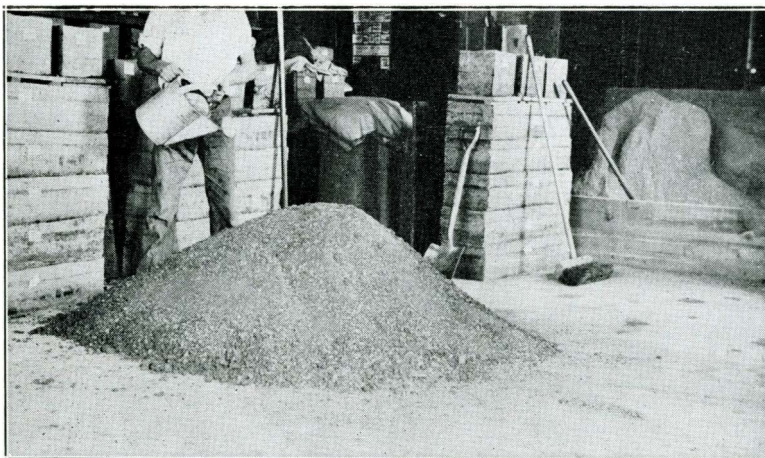


FIG. 7. ADDING MOISTURE TO SOIL FOR RAMMED EARTH WORK

Water is added to the soil from a garden sprinkler as the soil is turned. The picture is taken inside the research laboratory of the department of Agricultural Engineering, South Dakota Agricultural Experiment Station.

er than the second and third, but much better than the first. The important thing was, the too-wet wall was much better than the

too-dry wall. Later work has shown the importance of having the moisture high enough, rather than having it too low.

### Kind of Soil Best Adapted to Rammed Earth Construction

Contrary to the prevailing opinion, heavy clay soils and soils often referred to as "gumbo" are the poorest kind for rammed earth construction.

The most satisfactory soil for rammed earth construction will have a considerable amount of sand in it, ranging from 40 per cent to 75 per cent, with the optimum amount around 75 per cent. This will vary with soils of different analyses. The best test wall in the yard is made from soil having 74.8 per cent of sand in it.<sup>9</sup> The study has proved quite definitely that the sand or aggregate, when as high as 70 per cent is used, will have a somewhat greater strength in walls if it is well graduated from the fine particles up to the larger pebbles, with a majority of the finer aggregate. When there is such a graduation of aggregate the finest particles fit in between the larger sizes and the larger sizes fit into the spaces of the still

larger pebbles, and so on. The soil mentioned above, having 74.8 per cent of sand in it, contained sand that was exceedingly well graduated. It is the Experimental Soil No. 3, and the mechanical analysis of it is given in Table 1. This soil has the highest unit weight of any soil that has yet been found, averaging 138.87 pounds per cubic foot after being rammed.

Few natural soils containing less than 30 per cent of sand were found satisfactory for rammed earth construction, and 35 to 50 per cent was much better. Many agricultural soils will be found to fall in the group containing 30 to 50 per cent of sand and will be found satisfactory. Sand can be added to a

<sup>9</sup>Sand as used in this report includes all the hard aggregate that will not pass through the 200-mesh screen or will not float off when the soil is washed in a pan. Some of the pebbles may be almost as large as the fist, while the finest grains will just be retained on the 200-mesh screen.

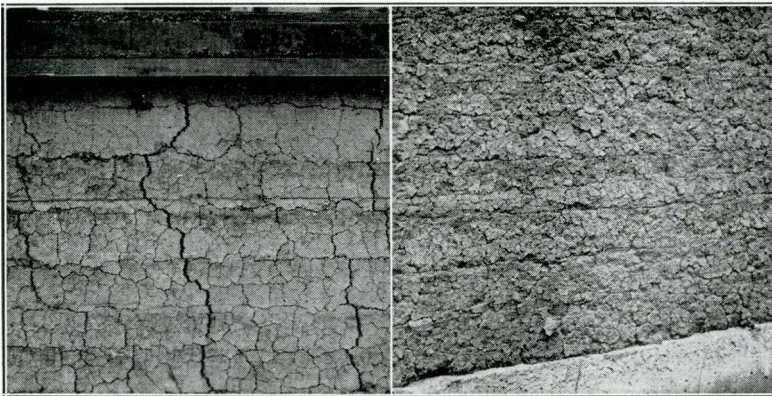
soil slightly deficient in sand with very little trouble. In fact, if the sand is convenient, it can be added on the mixing board with scarcely any additional labor, and it is advisable if at all possible. Very few soils with less than 50 per cent of sand will stand as a

bare wall, and 70 to 75 per cent is apt to be more weather resistant. Soils of medium quality can be used satisfactorily when stuccoed over bonding wire but the addition of sand will make it high quality and is recommended.

### **A Simple Test of Soil for Rammed Earth Work**

In spite of the fact that there is a wide range of soils that can be used successfully for rammed earth work when stuccoed, a good soil will require a little less care in ramming and, still more important, will stand longer in case the stucco is neglected after the building becomes old. As stated above, such a soil will have between 50 per cent and 80 per cent of sand in its structure. A simple test can be made to determine roughly whether a soil falls in the class of good soils or not. Take an average sample of the soil in a flat pan and dry it in a hot oven for three or four hours. A wash basin will answer perfectly for this purpose. The amount of soil should be more than a quart. Next, pulverize the soil fairly well so it will not have many lumps in it. Pebbles of all sizes should be left in the sample. Fill a quart cup with the dry soil and settle it

down so the cup is entirely full. Place the soil in a wash basin or other flat pan and cover with water, then stir with the hand and pour off the dirty water. Fill the pan with clean water and repeat this operation until all the fine silt and clay particles are floated off. It will only take a few minutes until all the silt and clay are gone and the water will remain clear. What is left in the pan will be clean sand and some of it will be very fine. Dry the sand and measure it in a measuring cup. If there is a full cup of sand there is approximately 30 per cent of sand by weight in the soil, and it is apt to be fairly good for rammed earth work. If there is more than a cup of sand and not more than three cupfuls it should be an excellent soil for the work. Laboratory analysis of soils is urged before building.



**FIG. 8. AN EXPERIMENTAL WALL OF HEAVY CLAY OR "GUMBO" SOIL**

This wall section shows extreme checking and cracking of an earth wall due to a very low sand content of the soil used.

At the right is the surface of the same wall several months later. The cracks settle together to quite an extent after the moisture leaves, but the wall crumbles away.

## **Effect of Reramming Soil in Pisé Construction**

Soil that has once been rammed into a structure can be broken up and used again if desired. A trial was made of this by ramming a test block of Experimental Soil No. 1. The block was tested for strength in the compression machine, being tested to destruction. After it was broken the pieces were broken up on the concrete floor of the testing laboratory by means of the rammers

and the soil was used again in making another block within a few hours. The second block was tested in the same machine and its strength was slightly higher than that of the original block, due, no doubt, to the anxiety of the operator to do a careful job of ramming. Only a slight amount of moisture was lost from the first block due to the remixing process.

## **Effect of Freezing Weather upon Rammed Earth Construction Work**

Construction work can be carried on in any reasonable weather as long as the soil is not frozen and the temperature does not fall too much below freezing. However, it is advisable to avoid freezing weather when possible. During the fall of 1930 a large wall section was being built at intermittent intervals throughout the month of November and up until Christmas time. Although the weather was generally mild, the temperature fell somewhat below freezing on several occasions, and with no evident injury to the wall. In January of 1933 a small weathering wall was rammed with the tempera-

ture at 18 degrees F. and zero temperatures followed within a few days. The temperature of the soil used in this wall was above 60 degrees F. when the wall was rammed, however, because the soil had been kept inside. This wall came out in excellent condition.

A small weathering wall rammed late in the fall of 1932 was caught by an extremely cold temperature that lasted for several days. This wall appears to have been injured by freezing as two large sections of it seem to have been moved out of line with the rest of the surface by the action of frost.

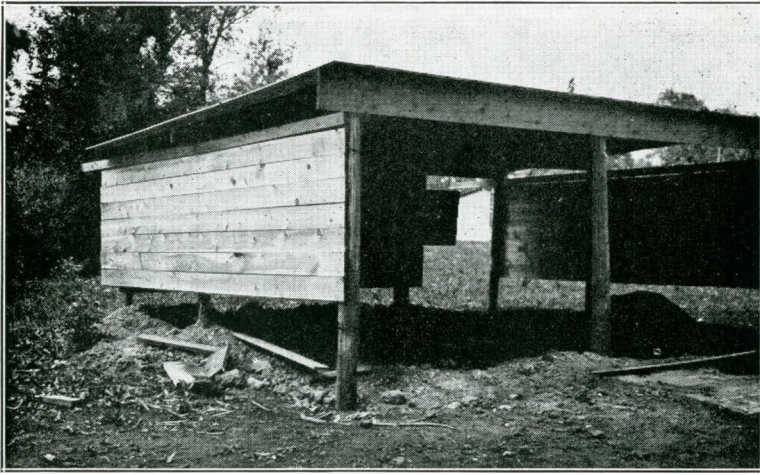
## **Care and Mixing of the Soil for Rammed Earth Work**

Care of the soil for rammed earth work is of greatest importance. The work can be done in almost any kind of weather if the soil is kept dry. Soil that is too dry can easily be corrected by sprinkling the pile with water and turning it carefully on the mixing board. It is better to do this the day before it is used, as the moisture will help to distribute itself in the pile during the night. A temporary shed as shown in Fig. 9 is almost a necessity if no other cover is handy. Sheeting lumber to be used for the roof of the building can be used in making this shelter. Another way to add moisture to soil that has become only slightly too dry under the shelter is to pile a load or two outside where it will get the rains. A few shovels of this damp soil with each batch shoveled on to the mixing board will secure the correct moisture. In adding moisture it will always save time if a certain number of shovelfuls

are used for each batch and a measured amount of water is added each time. In this way there is no guess work, and it is important to have the moisture content reasonably uniform.

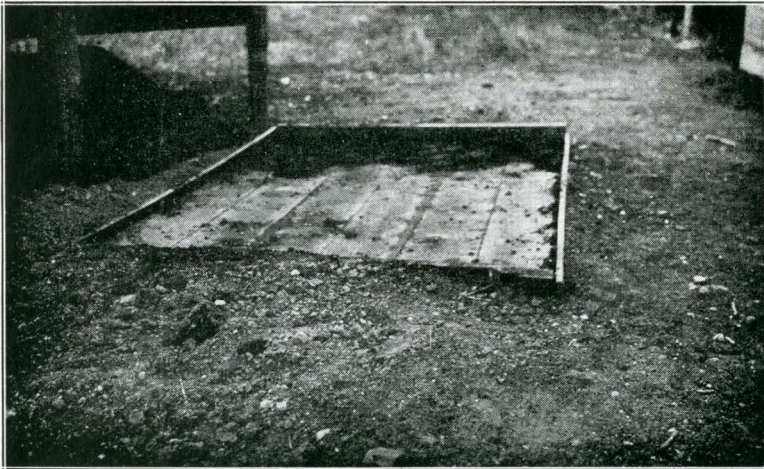
**Screening the Soil for Rammed Earth Work.** It is not necessary to screen the soil that is to be rammed unless there is some special reason for it. If there were large pieces of tree roots it would be desirable to screen them out, or if the soil contained hard dry clods it would be necessary to screen them out. A stone as large as a hen's egg would do no damage in the wall if there were not too many of them. All of the experimental soil used in making test blocks and test beams in the laboratory is screened. A concrete mixer was found satisfactory for mixing the soil when the moisture was nearly right.





**FIG. 9. A SHELTER FOR PROTECTING THE SOIL USED FOR RAMMED EARTH WORK**

In a shelter like this the soil can be kept dry enough to work at all times. A heavy rain on unprotected soil will make it too wet to use for days and even for weeks. If a shelter is not available a canvas or other protection is necessary. The lumber used in building this shelter was all used in the roof and plate construction after the walls were finished.



**FIG. 10. THE MIXING BOARD FOR THE SOIL**

A mixing board is very convenient for turning the soil when moisture must be added or when two or more different kinds of soil are mixed for use. The board is almost necessary when the ground is muddy. It is approximately six by ten feet.

## Effect of Depth of Block upon the Strength in Compression

Since it was found practically impossible to make the test blocks exactly the same depth or height, it was necessary to make corrections for the blocks when this difference was appreciable. In order to determine the exact ratio of the depth of the test piece to its compressive strength so as to determine the correction coefficient, a series of blocks was made varying the depth of the blocks in graduated amounts. Since the standard test blocks were rammed in four layers, each being a trifle over two inches in thickness, one series of blocks was made only one layer in depth, averaging 2.24 inches. A second series of blocks was made two layers in depth, averaging 4.4 inches. A third series of three layers averaged 6.675 inches, while a fourth series of the standard four layers averaged 8.9 inches in depth. The

strength varied inversely as the depth of the test piece. The four thinnest blocks were too strong for the 100,000 pound testing machine. The blocks having a depth of 4.4 inches averaged 662 pounds per square inch, those having a depth of 6.67 inches averaged 334, while those having a depth of 8.9 inches averaged only 191.5 pounds per square inch. Experimental Soil No. 3 was used. It is a very sandy soil and is not a strong soil comparatively, but in this series the blocks were all low in strength even for this soil as the blocks were still green. The figures are summarized in Table 4 below. The correction coefficient as figured from this test is 5.3 pounds per square inch for each tenth of an inch the test piece may vary above, or below, nine inches in depth.

Table 4. Effect of Depth of Test Block upon the Strength in Compression

No. of blocks of each tested	Depth of blocks (av.) in inches	Av. ultimate breaking load in lbs.	Compressive strength in lbs. per sq. inch	Age when broken (days)	Moisture content when made	Moisture content when broken	Weight of blocks in lbs. (average)
4	2.24	*	1,234.†	35	7.92%	0.33%	15
4	4.40	51,625	662.	35	7.92%	0.45%	30
4	6.67	27,050	334.	35	7.92%	0.85%	45
4	8.90	15,515	191.5	35	7.92%	1.32%	62

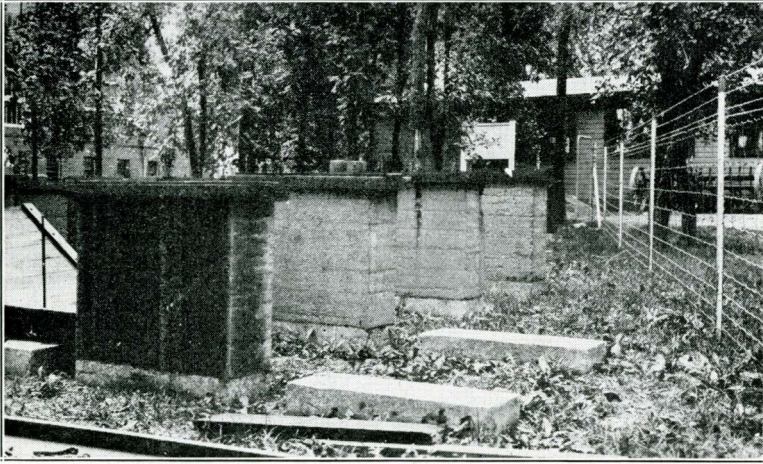
\*These blocks stood more than 100,000 pounds, which was the limit of the testing machine used.

## Resistance of Rammed Earth Walls to Weathering

In determining the resistance of a soil to weather action, small test walls were built of each different soil to be tested. These walls are 12 inches thick, 36 inches long and approximately 30 inches high. They are covered on top with a flat roof that projects 1½ inches on all sides. This type of roof was found unsatisfactory as the water in time of heavy rain is apt to flow back underneath this overhang and down the face of the bare wall. When this happens, grave damage is done as the flowing water cuts the earth surface like a knife. Quarter round was used to prevent the water from flowing underneath, but with a heavy wind there was still some injury from this source. The covers were

then edged with sheet steel strips with the lower edge of the strips projecting an inch below the plank, and this trouble was eliminated. It was not intended to protect the walls from direct rain action, but a peaked roof with the same projection would be more practical and more satisfactory for this purpose. The walls were built on concrete foundations, with exactly the same width as the walls, extending 12 inches below and 6 inches above grade. When the walls were built some of the foundations were covered with water-proofing materials and others were left untreated for the purpose of comparison. Ninety walls have been built up to this time in this weathering series. Corrected





**FIG. 11. A CORNER OF THE RAMMED EARTH EXPERIMENTAL YARD AT THE SOUTH DAKOTA EXPERIMENT STATION AT BROOKINGS, SOUTH DAKOTA**

This shows the type of small weathering wall used in the study. The roofs or covers as shown were not satisfactory, as heavy rains caused the water to run back under the roof projection and down the face of the wall in some instances. This cut the wall like a knife. A peaked roof would be better than the type shown. One hundred and thirty of these experimental walls have been built up to the present time.



**FIG. 12. FORM USED FOR MAKING RAMMED EARTH WEATHERING TEST WALLS**

The tremendous side thrust exerted by the soil while being rammed may be realized by noting the 2x4 inch struts on this form.



walls have been built to see if an addition of sand, or of clay, or an adjustment in moisture content would improve the original wall. For each wall made from a different type of soil a corrected wall has been built in the testing yard.

The study to date indicates that protective coverings for rammed earth walls are highly desirable if not absolutely necessary in this region, for any except the most favorable walls.<sup>10</sup> The best walls may be slightly roughened on the north side from driving rains, and most of the medium soils begin to crumble slightly within three years' time. A covering of some effective material such as a covering of cement plaster or stucco not

only protects the wall surface against ordinary weathering, but protects it against flowing water which might strike in an emergency, or in the case of an old roof that had been neglected.

For this same reason it is highly desirable that the tops of walls be protected under and around the plate with a thick layer of rich cement mortar. This mortar would also serve to level up the plate on the top of the wall. In the case of plaster or stucco on the outside surface, this should be delayed until the wall has dried out.

<sup>10</sup>New walls weather more rapidly. After one or two years the walls made from favorable soils become very resistant and are affected very little by the hard driving rains.

### Protective Outside Coverings for Pisé Walls

Since the subject of protective coverings is thoroughly reported in South Dakota Experiment Station Bulletin 336 entitled "Paints and Plasters for Rammed Earth Walls," most of the report on these materials included in the first and second edition of bulletin 277 has been omitted in this edition. Coverings that were found satisfactory on exterior walls were few, while most

coverings proved entirely satisfactory for interior surfaces.

**Stucco:** For exterior surfaces Portland cement stuccoes have proved entirely satisfactory for rammed earth walls. The same bonding wires that are used for frame walls have been used. These include stucco wire metal lath and other expanded metals. The wire is nailed directly into the wall in such a



FIG. 13. THIS GARDEN WALL OF RAMMED EARTH WAS BUILT IN 1934 AND WAS STUCCOED IN 1935

The soil used in the wall is only medium in quality and, hence, must have a protective covering. The picture was taken before stuccoing. The wall is an experimental wall and today carries 28 panels on which different methods of bonding the stucco to earth walls are being tried.

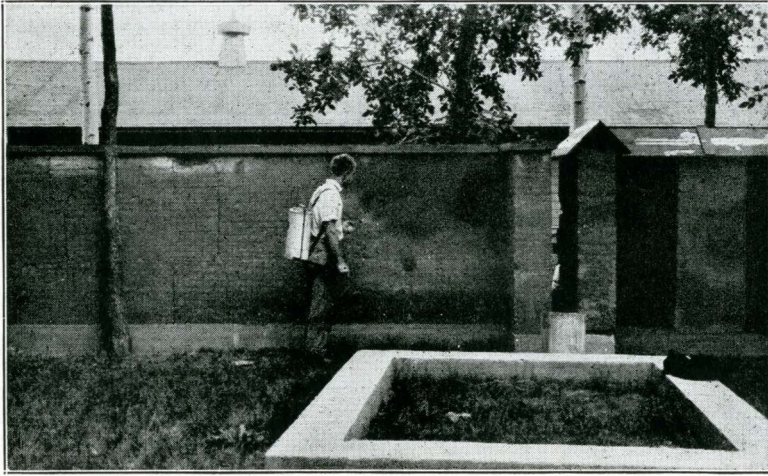


FIG. 14. WETTING DOWN A RAMMED EARTH WALL BEFORE PLASTERING

Before plastering the earth wall, it is wet down so that the moisture will not be drawn from the plaster. A garden sprinkler or hose could be used in place of this small spray machine.

manner as to stretch the wire and carry the weight of the stucco. The strips of wire must be lapped and wired together firmly according to ordinary specifications for stucco work. The wire should be nailed with 10d and 16d nails spaced approximately 12 inches apart and at random. This method of securing the bonding wire proved most satisfactory of many methods that were tested.

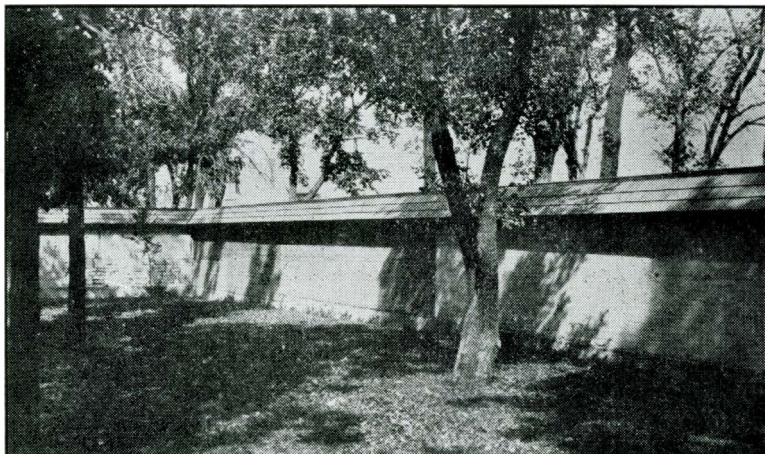
In studying ways of reducing costs on small farm buildings, several methods of securing the stucco without the use of bonding wire were tested. Results show that for low walls with occasional openings the bonding wire can be omitted if the nailing is carefully done. The method used was as follows: After the wall surface was swept down and sprayed with water the scratch coat (first coat) of stucco was applied. Following the stucco man immediately, a man drove nails through this fresh stucco into the wall. The wall was then allowed to stand for three days to three weeks and the second coat of stucco was applied. A third or finish coat can be used if desired or this second coat can be sand finished with a carpet float. No attempt should be made to apply extra thick coats of

stucco. Ordinary thickness is better as the expansion forces will be less. Two coats only were used in the experimental work. This method of bonding with nails only is not advised for important work such as dwelling houses.

**Less Expensive Plasters:** Work has been done with many new and less expensive plasters for use on low cost buildings. This work is reported in bulletin 336. Two of these plasters that have stood satisfactorily are dagga-cement plaster and asphalt emulsion plaster. In the first one a dagga plaster is stabilized by adding 10 per cent of Portland cement by volume; the second one is stabilized by adding asphalt emulsion at the rate of one gallon of asphalt emulsion to 100 pounds of dry dagga mixture. Dagga plaster is a mixture of medium sandy clay and sand in a ratio of one part of the clay soil to two parts of plaster sand. Including the sand in the clay, the actual ratio of clay is approximately one to three.

**Paints:** Of the actual paints that have been tested for exterior surfaces, none have proved sufficiently dependable for general recommendation. On high quality walls





**FIG. 15. AN EXPERIMENTAL WALL FOR PAINTS AND PAINTING METHODS**

This garden wall is divided into 28 experimental paint panels. The paints were applied at different periods, in different weight and number of coats, and over different priming coats. Different soils were also used, varying from excellent to very poor in quality.

good quality lead-oil paints will stand for periods up to five or six years but some of these failed later after repainting. Casein paints applied in 1939 are standing satisfactorily after six years. When paints fail on earth walls the surface is roughened. Artists

like this roughened surface for dwelling houses. In case builders agree with the artists, paints may be used on walls with high quality soils. In case it is desired to change a painted surface to one of stucco, the paint coat must be entirely removed.

### **Inside Wall Coverings**

Probably any satisfactory covering for other surfaces can be used on interior walls of rammed earth. They can be applied directly to the earth surface. Both oil paints and cold water paints have been successfully used. All ordinary plasters were found entirely satisfactory. The scratch coat of plaster should be nailed with 10d nails in the

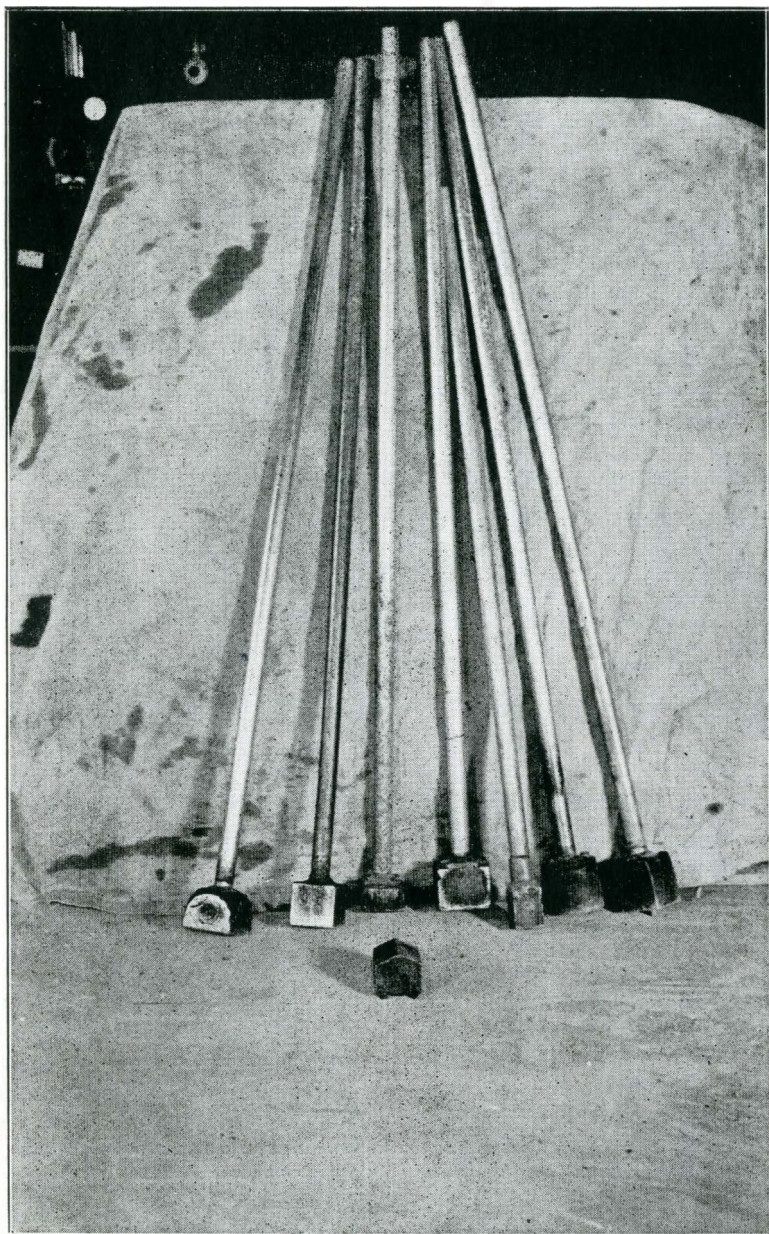
same way as for stucco on exterior walls of low cost buildings. The only two failures with inside wall coverings that have occurred have been with a special wood fiber plaster and whitewash—a cold water paint. Murescoes are quite satisfactory. They, as well as oil paints, were applied over a glue sizing or linseed oil sizing coat.

### **Weight, Shape and Type of Hand Rammers**

After three years' experience in the use of hand rammers of various shapes, sizes and weights, the favored rammer was one with a cast iron or steel head cubical in shape and approximately 3 inches in dimension each way. The shaft of this rammer will be of one-inch galvanized iron water pipe and approximately 5 feet 6 inches long. The total weight of this rammer will vary from 13 to

18 pounds. The face of the rammer will be perfectly smooth and flat, and the weight of the rammer will be from 1.5 pounds to 2 pounds for each square inch of the rammer face. This rammer will be well balanced with a shaft easy to grasp and hold and one that will quickly wear to a very smooth surface. The inch pipe may be threaded and screwed into a plate made from a pipe flange





**FIG. 16. A COLLECTION OF HAND RAMMERS USED IN BUILDING RAMMED EARTH WALLS**

The square, flat-faced rammer, weighing from 15 to 18 pounds, is preferred by the workmen. The shaft is made from one inch galvanized pipe. The rammer head shown in the foreground has a beveled face, the sides making an angle of 30 degrees with the horizontal. Workmen did not like to use this rammer and test pieces made with it were not as strong in compression as those made from the flat-faced rammer.\*

\*See Table 5.

that is, in turn, fastened to the iron block by means of screw bolts, or the pipe may be brazed or welded to the head. Welding the shaft to the head will be best when the materials are suitable, as the flanges will fail after long use. The square rammer is favored because corners and edges of the form can be better reached with it and the flat rammer is not only favored by the workman but test pieces made with the flat-faced rammer have shown a greater average strength in compression.

In order to compare the effectiveness of the flat-faced rammer with those having sharp faces, a careful test was made. Three

shapes of rammer faces were used. One<sup>11</sup> has a sharp face in which the sides make an angle of 45° with the horizontal, one has a fairly sharp face in which the sides make an angle of 30° with the horizontal, and the third has a flat face. Five test blocks were made with each rammer and tested to failure in a compression machine. An identical soil, test Soil No. 2, having a total sand content of 37.5 per cent, was used and the moisture content was kept uniform. The blocks made with the flat rammer were strongest, those with the 30° rammer averaged next in strength, and those with the 45° rammer showed the least strength. These results are shown in Table 5.<sup>12</sup>

Table 5. Comparative Strength of Test Blocks Rammed with Different Shaped Rammers (Compressive Strength)

Shape of rammer face	Ultimate load of test blocks in compression (average)	Compressive strength lbs. per sq. inch	Age when broken (in days)	Total sand content (per cent)	Number of blocks of each broken
Sharp-faced rammer					
Sides 45° with horizontal .....	28,457	351.3	40	37.2	5
Sharp-faced rammer					
Sides 30° with horizontal .....	40,219	496.5	40	37.2	5
Flat-faced rammer .....	44,107	544.5	40	37.2	5

The beveled rammer heads used and described in the early work with rammed earth proved both unsatisfactory and unnecessary.

### Intensity of the Tamping Stroke

A study was made to determine the effect of the intensity of the ramming stroke upon the compressive strength of rammed earth. Test blocks were made in the standard form. Five blocks were made using light strokes, five were made using medium strokes, and five were made using heavy strokes. A supply of soil was carefully prepared for these blocks containing 38.22 per cent of total sand and 61.78 per cent of silt and clay by weight. This is very nearly an average soil and contained 9 per cent of moisture when used. This moisture was perhaps slightly under the optimum amount. The blocks were rammed in four layers of equal weight, making the weight of the finished blocks almost identical. The depth of the finished blocks varied inversely with the intensity of the tamping stroke used in making them (see Table 6). Approximately 100 strokes were used in tamping each layer, although a

fewer number would have been sufficient for the harder strokes. For the light strokes the rammer was raised about four inches and no exertion used in making the stroke. For medium strokes the rammer was raised about six inches and very little pressure was applied. For the heavy strokes the rammer was raised about 12 inches and all the force possible applied with the stroke. As shown in Table 6, the compressive strength of the blocks varied directly with the intensity of tamping and was decidedly in favor of

<sup>11</sup>See Figs. 16 and 17.

<sup>12</sup>It is true that with flat-faced rammers the planes of cleavage between layers of earth in the walls are quite apparent and the shearing strength is probably less than if wedge-shaped rammers are used, yet the strength in compression was greater and the stability was found definitely adequate. No trace or suspicion of failure has developed in any of the more than 1,000 feet of walls that have been built during the past 15 years either in straight experimental walls or in buildings. One experimental building has been constructed with a roof truss that throws a maximum roof thrust upon the rammed earth walls. The walls are standing perfectly after ten years.

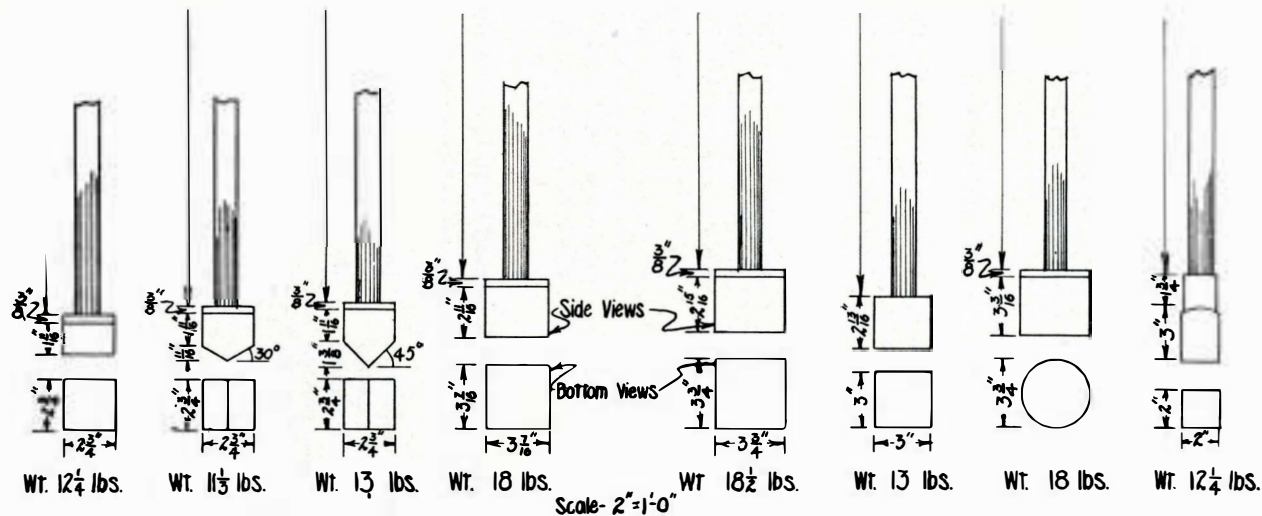




Table 6. Effect of Intensity of Tamping Stroke upon Strength of Rammed Earth

Number of blocks of each tested	Intensity of stroke	Av. ultimate breaking load in pounds	Compressive strength lbs. per sq. in.	Depth of blocks when made (av.)	Weight of blocks when made (av.)	Unit weight per cu. ft.	Moisture when broken (av.)	Age when broken (days)
5	LIGHT	7,506	92.7	11.14 in.	56 lb.	108	2.1%	44
5	MEDIUM	15,320	189.1	9.97 in.	56 lb.	125	2.7%	44
5	HEAVY	36,280	393.4	8.94 in.	56 lb.	135	2.9%	44

Walls rammed with medium intensity have proved definitely satisfactory in the 15 years of study.

the heavy tamping. The five lightly tamped blocks averaged 92.7 pounds per square inch in compression. The five medium tamped blocks averaged 189.1 pounds per square inch, while the five heavily tamped blocks averaged 393.4 pounds per square inch. Extremely heavy strokes are not necessary for rammed earth construction, although it might show a slight increase in the strength of the wall, but this study indicates that some little pressure is needed on the rammer especially near the beginning and at the end of the tamping of a new layer. If pressure is not used the bottom of the layer will not be compressed sufficiently. It is entirely probable that the weathering resistance of the

wall will also be greater for the heavier tamping, and especially so if no protective covering is used. On the other hand the more lightly tamped wall would be the best insulator.

The strength of the blocks ran quite uniformly for each group, seldom varying more than 10 per cent from the average figure. One exception was with one of the blocks made with a medium tamping stroke. This block tested only 82.90 pounds, which was only half the average strength and probably due to some unnoticed defect. It was averaged in with the rest as it would affect the average figure but slightly.

### Size of Aggregate in Soil for Rammed Earth Construction and Its Effect upon the Compressive Strength

The fact that a considerable amount of aggregate is desirable in soil for rammed earth work led to this study to determine the effect of different sizes of aggregate in rammed earth walls. Experimental Soil No. 1 was used for the base soil. It originally contained 10.4 per cent of fine aggregate. This base soil was mixed with sufficient moisture to bring the moisture content up to 16.01 per cent. The aggregate that was added was then moistened before it was mixed with the soil for ramming into the form. In having the base or bonding soil at the same moisture content and in moistening the aggregate before mixing, it was believed that the results would be most comparable. This accounts for the decidedly higher moisture content in the check blocks because the addition of aggregate reduces the moisture content decidedly. The larger sized aggre-

gate having less surface area reduced the moisture more than the smaller sizes, as shown in Table 7.

Two different series of blocks were made for this study. In the first series, made more than a year earlier than the second, only three different sizes of aggregate were used. Thirty-five per cent (by weight) of aggregate was added to the 10 per cent already in the base soil in each instance, bringing the total up to 45 per cent. Four standard sized test blocks, each 9x9x9 inches high (approximately), were made for each different sized aggregate, viz., four with aggregate ranging in size from 0 to one-eighth inch, four with aggregate ranging in size from one-eighth to one-fourth inch, and four with aggregate ranging in size from one-fourth inch to one-half inch. The figures are given in Table 7 along with the figures from the

more complete similar series for the purpose of showing the similarity in results.

The second series of blocks for this study was made in the same way using the same base soil. In the second series 35 per cent of aggregate was added as in the first series and two additional sizes of aggregate were included. The blocks were tested to destruction in a Riehle testing machine, described earlier in the bulletin. Owing to the nature of the surface of the test blocks it was impossible to read the point of incipient failure with sufficient accuracy, so the ultimate load only is given. Space will not permit showing the strength figure for each individual block but they showed a surprising uniformity of strength for each series, varying only slightly from the average figure. The soil having the one-eighth to one-fourth inch sized aggregate showed the greatest strength. The 0 to one-eighth inch size was second in strength. The check blocks with no added

aggregate came third in strength and the others came in the following order: one-half to three-fourths inch, one-fourth to one-half inch, and three-fourths to one and one-half inches. The only variation in the curve was in the size one-half to three-fourths inch going above the one-fourth to one-half inch size in strength, although these two were very nearly the same. The figures bring out the unquestioned fact that aggregate in rammed earth soils up to one-fourth inch in size and in quantities up to 45 per cent will increase the compressive strength of the structures. It also clearly shows that aggregate larger than one-fourth inch in size, although desirable in reasonable quantities, will decrease the strength of rammed earth structures when used in quantities as high as 35 per cent.<sup>13</sup>

<sup>13</sup>Although the size of aggregate affects the compressive strength of pise' walls it seems to have no effect upon the weather resistance. Very fine sandy soils have proved highly resistant to weathering. Their strength is entirely sufficient for walls of reasonable height.

Table 7. Effect of Size of Aggregate in Soil on Compressive Strength of Rammed Earth

Number of blocks of each tested	Weight of blocks —lbs. av.	Moisture content when made	Moisture content when broken	Total aggregate in soil	Age when broken (days)	Size of aggregate added (35%)	Average ultimate breaking load in lbs.	Compressive strength in lbs. per sq. in.
<b>First Series</b>								
4	56.2	12.89%	3.88%	45%	54	0 in. to 1/8 in.	28,956	359
4	55.8	12.45%	4.06%	45%	54	1/8 in. to 1/4 in.	31,428	388
4	55.7	13.31%	4.28%	45%	53	1/4 in. to 1/2 in.	26,804	330
<b>Second Series</b>								
4	43.6	16.01%	6.21%	45%	60	None	23,757	293
4	54.6	12.04%	3.38%	45%	60	0 in. to 1/8 in.	25,345	313
4	53.8	11.51%	3.43%	45%	60	1/8 in. to 1/4 in.	27,010	333
4	54.2	11.22%	3.82%	45%	60	1/4 in. to 1/2 in.	17,452	216
4	54.8	10.8 %	4.01%	45%	55	1/2 in. to 3/4 in.	18,547	229
4	54.7	11.81%	4.28%	45%	60	3/4 in. to 1 1/2 in.	13,370	165

## Effect of Adding Lime

A brief study was made to determine the effect of lime on rammed earth. Pure hydrated lime was used and mixed with a carefully prepared soil made up of 62.5 per cent silt and clay, 37.5 per cent total sand and with 10 per cent moisture. To the lime was added just enough moisture to give it the same apparent moisture as the soil. A care-

fully weighed amount of lime was added to give each series of test blocks the following percentage of added lime: Three blocks with 1% of lime, three blocks with 2% of lime, three blocks with 3% of lime, three blocks with 4% of lime, three blocks with 5% of lime, three blocks with 10% of lime, and three blocks containing no lime for

checks. The blocks were rammed in four layers. Fourteen pounds of the mixture was weighed for each layer of the blocks and the final blocks averaged approximately 56 pounds each. The test blocks were rammed on November 26 and December 3, 1932, and broken on January 7, about five weeks later. During this interval they were stored in the research laboratory under a temperature of approximately 70° F. where the moisture was reduced to an average of slightly over 3 per cent, as shown in Table 8. The added lime had the effect of causing the corners and edges of the blocks to crumble slightly and seemingly in direct proportion to the amount of lime added. This effect was so pronounced as to make the blocks delicate to handle, especially when they were removed from the trays and placed in the testing ma-

chine. The blocks were tested to failure in a Riehle machine to determine the effect of the added lime on the compressive strength of rammed earth. The operators used in ramming the blocks were interchanged when each layer was partly rammed, thereby eliminating any chance for a variable from this factor. The strength curve was not quite uniform, as the table shows, but there is no doubt that the lime weakened the test blocks, as the check blocks which contained no lime were decidedly stronger. It is probable that the increment between the amounts of lime added should have been greater. Slight corrections were made for difference in the depth of blocks, which in no case changed the order of the resulting strength figures. The results are summarized in Table 8.

Table 8. The Effect of Adding Lime Upon the Strength of Rammed Earth Test Blocks  
(Dimensions of Blocks 9 in. x 9 in. x 9 in.)

Number of blocks of each tested	Amount of lime added in per cent	Average ultimate breaking load in pounds	Compressive strength in lbs. per sq. in.	Kind of soil used		Moisture when made	Moisture when broken
3	None	42,500	524	Silt and Clay	61.78%	10%	2.1%
				total Sand	38.22%		
3	1%	32,260	404	"	"	10%	2.6%
3	2%	27,250	356	"	"	10%	3.7%
3	3%	34,460	436	"	"	10%	3.4%
3	4%	33,340	435	"	"	10%	3.9%
3	5%	28,590	377	"	"	10%	2.0%
3	10%	30,760	405	"	"	10%	3.1%

### Effect of Mixing Fiber with Rammed Earth upon Its Strength in Compression

A total of 28 test pieces was made for this study. Experimental Soil No. 2<sup>14</sup> was used for the base soil and the blocks were of standard size—9x9x9 inches. Corrections were made for slight differences in depth of blocks. These corrections made no difference in the comparative order of results. Three different kinds of fiber were added to these blocks, viz., flax straw, oat straw, and grass roots. A series of three blocks was made to which the flax straw was added. The straw was cut up roughly into lengths of about five inches. All the straw that could be mixed into the soil without having it form in bunches was incorporated. Three

blocks were made in the same manner using oat straw, and four were made using the grass sod. This series of blocks was then repeated using approximately one-half the amount of the same fibrous materials in the soil. Eight check blocks were made containing no fiber and compared to the above blocks in compressive strength. The blocks containing the maximum fiber gave the greatest strength, or 438 pounds per square inch. Those containing one-half of the maximum fiber came next in strength with an average of 370 pounds per square inch,

<sup>14</sup>See Table 1.



Table 9. Effect of Mixing Fiber with Rammed Earth Upon Its Strength in Compression  
(Dimensions of Blocks 9 in. x 9 in. x 9 in.)

Number of blocks of each tested	Kind of soil used	Moisture when made average	Moisture when broken average	Age when broken	Amount of fiber added	Compressive strength in pounds per sq. in.
3	Silt and Clay 61.7% Total Sand 37.2%	8.93%	3.60%	46 da.	Maximum Oat Straw	485
3	" "	8.93%	2.04%	46 da.	Maximum Flax Straw	473
4	" "	8.71%	1.70%	53 da.	Maximum Grass Sod	357
					Maximum Fiber Av.	438
3	" "	8.93%	3.39%	46 da.	½ Maximum Oat Straw	429.6
3	" "	8.93%	3.30%	46 da.	½ Maximum Flax Straw	381
4	" "	8.71%	2.15%	53 da.	½ Maximum Grass Sod	299
					½ Maximum Fiber Av.	370
8	" "	8.71%	1.66%	53 da.	None	325

while the check blocks containing no fiber showed the least strength with 325 pounds per square inch. All factors such as ramming, moisture content and base soil were closely controlled. This study would indicate that there is some increased strength to be expected from adding fiber to the soil in rammed earth work. In most cases there should be no need for it, however, and the fiber spoils the smoothness of the wall. It would interfere with some coverings that

might be used and if no covering was used it would probably cause more rapid weathering of the wall surface. This finding agrees with the following statement made by Long of California in Exp. Sta. Bulletin No. 472 —“With an alluvial loam soil, an admixture of approximately one-fifth part of straw by loose volume gave an increased strength amounting to 80 per cent in small specimens.” This is being studied. The data are summarized in Table 9, above.

### Rate of Drying Out of Rammed Earth as Affected by an Admixture of Fiber Such as Straw

Observation of test pieces of clay soils in which straw and other fibrous materials had been incorporated seemed to show less cracking and checking as they dried out. The logical reason for this seemed to be that the straw extending from the center to the outside of the blocks carried the moisture from the center of the block more rapidly than for those containing no straw. Heavy clay soils crack and check on the surface because the moisture from the outside

layers is lost, causing this portion to shrink first. If the moisture was lost from the center of the block or wall at the same rate as for the surface, the cause for cracking would be removed.

This study was made to determine if an admixture of straw in pise' walls would aid in leading the moisture from the center to the outside of the wall and thereby reduce surface cracks and, if so, at what rate as compared to walls with no straw. As is shown in

Table 10 and by the curves in Fig. 18 the results indicate definitely that the straw does not reduce surface cracks by aiding the escape of moisture from the center of the wall. It has no appreciable effect upon the rate of drying out or moisture loss from the wall.

In the plan for this study three clay soils were selected and three test pieces were made in each case, from which the average of the three pieces is recorded in the table and curve. Soil No. 1 is fairly heavy, black clay soil containing 40.4 per cent total clay colloids. The Pierre clay is a very heavy gray clay soil containing 50 per cent total clay colloids. Soil No. 2 is a medium yellow, sandy clay containing 37.3 per cent total clay colloids. Three "check" blocks were rammed from each soil without any admixture and three blocks were rammed from each soil to which was added all the straw that could be thoroughly incorporated into it. The amount was approximately 130 pounds of straw to 1000 pounds of soil. Oat straw was used and it was cut in lengths not

to exceed six inches. The test blocks were all made on the same day and the moisture used in the clay was just slightly above optimum. The blocks were weighed immediately as they were taken from the form and placed on an air-dried board tray of known weight. They were then held at constant room temperature and weighed at the intervals shown in the table. They were handled on trays, and tray and all was weighed each time to avoid the loss of any of the material. The loss of moisture only is recorded in the table for purpose of simplification and the loss is recorded in pounds. The moisture loss ran uniformly with each individual test block and the very slight difference in the rate of moisture loss was as apt to be in favor of the check block as with the block containing the straw admixture. Since this study indicates that moisture loss is not affected by the straw, and since it is quite evident that an admixture of straw does reduce cracking, it is therefore logical to assume that the straw takes up or absorbs a considerable amount of the shrinkage stresses due to its mechanical cushioning effect.

Table 10. Summary Sheet for Data and Curve on Rate of Drying Out as Affected by Fiber Admixtures

Date weighed	Soil No. 1 medium clay* loss of weight in lbs. to date—col. 1		Pierre clay—very heavy* loss of weight in lbs. to date—col. 1		Soil No. 2 light clay* loss of weight in lbs. to date—col. 1	
	Av. of 3 blocks with straw	Av. of 3 blocks without straw	Av. of 3 blocks with straw	Av. of 3 blocks without straw	Av. of 3 blocks with straw	Av. of 3 blocks without straw
Feb. 24, '34	(Date Rammed)	(Date Rammed)	(Date Rammed)	(Date Rammed)	(Date Rammed)	(Date Rammed)
Feb. 27	2.12	2.01	1.58	1.75	1.94	2.02
Mar. 3	3.35	3.45	2.77	2.96	3.15	3.11
Mar. 5	3.95	4.07	3.34	3.50	3.57	3.55
Mar. 8	4.47	4.64	3.81	3.97	3.98	3.88
Mar. 11	4.87	4.98	4.10	4.30	4.23	4.14
Mar. 20	5.73	5.78	4.92	5.03	4.80	4.60
Mar. 23	5.95	6.02	5.10	5.20	4.92	4.74
Mar. 26	6.15	6.21	5.24	5.35	5.02	4.81
April 1	6.31	6.41	5.42	5.25	5.10	4.94
April 9	6.60	6.61	5.57	5.62	5.23	5.04
April 18	6.79	6.81	5.73	5.80	5.32	5.16

\*A description of these three soils is given above.

## Reinforcing in Rammed Earth Construction

For the purpose of comparing the value of different kinds of reinforcing materials that might be used in rammed earth construction, 51 short beams were made, using eight different reinforcing materials. Seven of these beams were defective or broken in the making or hauling and were thrown out of the test. Three of these were the ones in which the use of boards was attempted. The test beams were 36 inches long, 12 inches wide and  $7\frac{3}{4}$  inches in depth. They were rammed from Experimental Soil No. 2, having a total sand content of 37.5 per cent and a moisture content averaging 10 per cent when the beams were made. The beams were rammed in three horizontal layers or laminations with the reinforcing material embedded in the bottom layer at approximately one and one-half inches from the

bottom of the finished beam. They were rammed in the bottom of the form that was built for making the small weathering walls.<sup>15</sup> A concrete floor furnished the bottom of this form. The reinforcing was placed in the following manner: The soil for the first or bottom layer of the beam was first weighed out. Enough of this soil was then shoveled into the form to make a layer of loose soil two and one-half inches deep. This soil was then leveled off and the reinforcing laid on top and pressed down slightly. The remainder of the soil for the layer was then shoveled in and the layer rammed. The other two layers were then rammed on top of this one, giving a total depth of  $7\frac{3}{4}$  inches for the beam. Two forms were used and two beams were rammed at the same

<sup>15</sup>See Fig. 12.

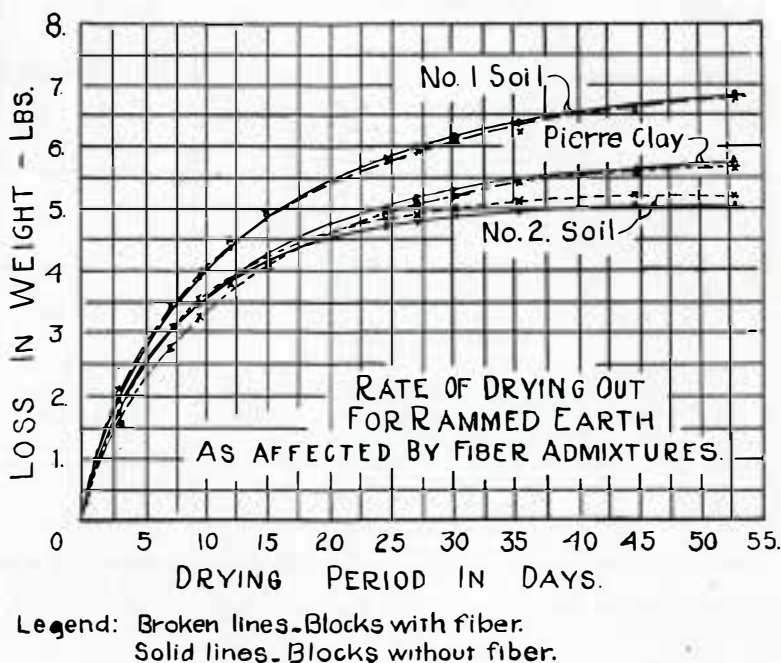


FIG. 18. THE ADDITION OF STRAW TO WALLS OF PUDDLED EARTH DOES NOT AFFECT THE RATE OF MOISTURE LOSS FROM THE WALL

The 9x9x9 inch test pieces of three different soils dried out at the same rate regardless of the admixture of straw. Note the close proximity of broken and solid lines in the curves for each soil.

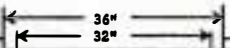


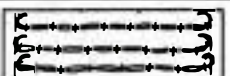

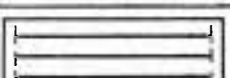
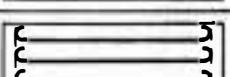
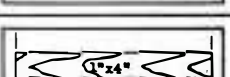


time. This allowed for the interchange of workmen on each layer in order that any difference due to the ramming factor would be reduced to a minimum. The first trial was made with three beams for each kind of

reinforcing. The second trial was made with five beams for each kind of reinforcing except that the beams with barbed wire with straight ends were not repeated. The second trial checked very closely with the first one

Table 11. A Comparison of Reinforcing in Rammed Earth Beams

(All beams 7 ¾ in. x 12 in. x 36 in.)

No. of Beams Tested	Kind of Reinforcing	Manner of Placing	Ultimate Breaking Load in Pounds. Average	Maximum Moment in Foot Pounds. Average	Average Moisture When Broken
8	None		740	370	4.32
7	Metal Lath		458	229	3.89
3	Barbed Wire		643	321.5	3.3
7	Barbed Wire		978	489	4.59
7	¼" Round Rods		1091	542.7	5.01
5	¼" Round Rods		1156	548	4.28
7	½" Round Rods		1757	878.5	3.94
	Boards Laid Flat				

No results were obtained on the beams reinforced with boards owing to the fact that difficulty was experienced in keeping the beams intact for testing.

NOTE: As a result of the work with reinforcing at this Station it was concluded that the use of lintels is much more efficient for reinforcing over openings. They should be made of reinforced concrete beams the same as for brick walls. Corner reinforcing with boards as mentioned in early writing will reduce the stability of the wall rather than increase it. If corners are to be reinforced, steel reinforcing rods are recommended. In continuous walls no reinforcing has been used in corners at the Station and no sign of failure has been experienced. When two earth walls join, reinforcing rods are recommended.

throughout, and the results of both trials are combined and recorded together in the table. The beams averaged 256 pounds each, in weight, when they were rammed and they were handled on narrow slat trays approximately four feet long by ten inches wide.

They were broken in an Olsen testing machine as shown in Fig. 2. They were supported on two pieces of two-inch pipe which were placed exactly 24 inches on center, making the bearing points exactly two feet apart, and making the span two feet. A third short pipe was laid on the top of the beam exactly midway between the supports, and the pressure was applied at this midpoint until the beam failed. An attempt was made to read the incipient load but fine checks that are often already present in earth beams made this figure somewhat uncertain and no figure is recorded in the table for it. For the check beams in which there was no reinforcing, there was very little deflection as the load was applied until the point of rupture was reached and the beams broke rather squarely across. For the reinforced beams there was a very noticeable bending of the beam before failure. In most cases the deflection was sufficient to shear the layers of earth apart at the planes of cleavage which occur between each successive layer of the beam as it is made. Since the beams were supported in the test at a point six inches from the ends and since the

strength figures desired were for comparative strength only, the weight of the beams was not included in the figures for the maximum moment. Two kinds of reinforcing materials that were tried decreased the strength of the beams materially. The beams with metal lath showed an average maximum moment of 229 foot pounds, while the three strands of barbed wire with straight ends gave an average figure of 321.5 foot pounds as compared to 370 foot pounds for the check beams in which no reinforcing was used. All the other kinds of reinforcing, except the boards, increased the strength of the beams materially and the strength varied as follows: Three strands of barbed wire with ends hooked, 489 foot pounds; three one-fourth inch round rods with ends hooked, 542.7 foot pounds; three one-fourth inch round rods with ends straight, 548 foot pounds; three one-half inch round rods with ends hooked, 878.5 foot pounds. Hooking the ends of the barbed wire increased the strength, while in the case of the rods there was no advantage shown. The figures are summarized in Table 11 and the arrangement of the reinforcing is also shown. Experimental Soil No. 2 was used in making these beams and a mechanical analysis of this soil is given in Table 1. The boards which have been mentioned in early writings on this subject not only reduced the strength by the greatest amount but in most cases caused the beams to crack and fail before the test.

### **Foundations for Rammed Earth Walls**

The study has shown the necessity of solid masonry foundations for rammed earth walls. If moisture soaks into the wall the physical structure of the soil changes. Results are shown in Fig. 38, p. 58. The wall will tend to expand and soften in much the same manner as a hard clod of dirt will soften after a rain except, of course, very much more slowly. A foundation is necessary to

prevent capillary moisture from entering it from below. The wall is heavy, weighing on an average of 120 pounds per cubic foot, and the foundation must be strong. The foundation must also be as wide at the top as the thickness of the wall. All foundations used have been of concrete and have been found very satisfactory. Since rammed earth walls are 12 to 24 inches in thickness, and since

the foundations should be the same thickness, such foundations will be expensive to build. It has been generally recommended that foundations in frost areas extend below the frost line for rammed earth walls. For dwelling houses and large buildings this

practice should be followed. Steel reinforcing rods are also recommended in the footings for such buildings. Thick foundations of such depth would be almost prohibitive in cost for small farm buildings. Tests were made to determine how deep a foundation

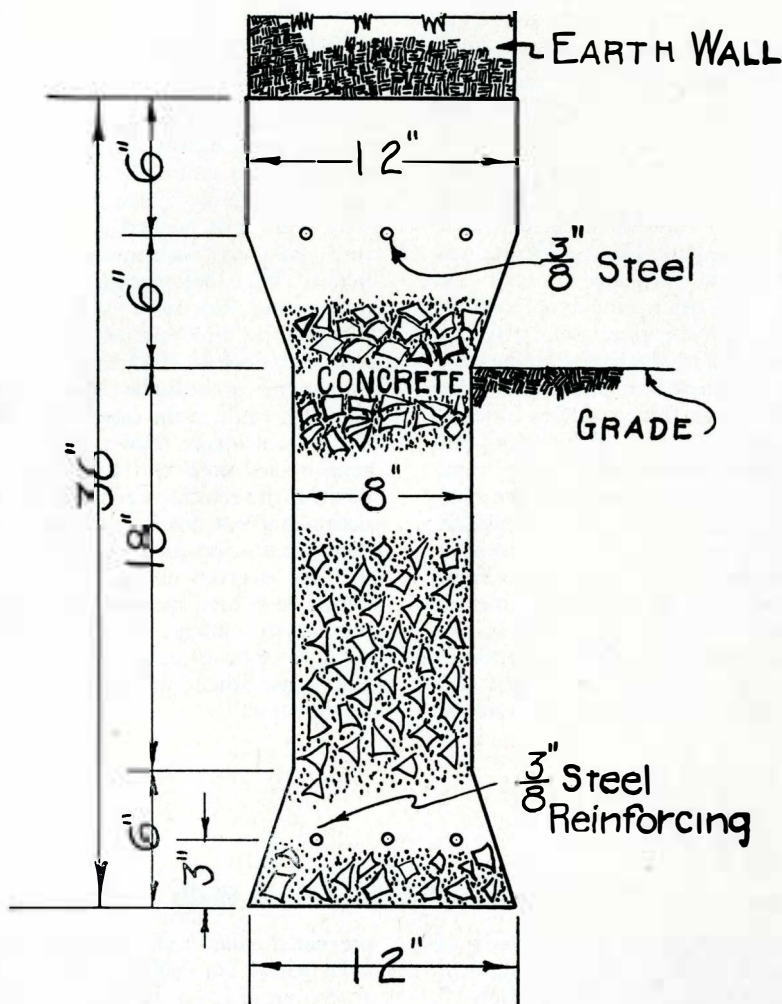


FIG. 19. A TYPE OF CONCRETE FOUNDATION BEING TRIED OUT UNDER LIGHT PISE' WALLS

Since the top of the foundation must be as wide as the earth wall, a saving of concrete can be made by reducing the thickness of the foundation between the top and the footing. For walls over 8 ft. in height the full width should be carried down from the top of the foundation more than 6 inches. This distance should increase slightly with the height of the wall.



of concrete is necessary in this region. Another test was made for reducing the cost of foundations for light buildings by using an 8 inch foundation widened at the bottom for a footing and widened again at the grade line to the thickness of the wall. The plan is shown in Fig. 19 and no absolutely definite conclusions have been drawn as to its practicability. However, no disadvantages are evident as yet.<sup>16</sup> Foundations should extend 12 inches above the ground.

**Waterproofing the Tops of Foundations.** There is no question but that the rammed earth wall must be protected from capillary moisture which might enter the wall from below. In the study an attempt was made to compare methods of waterproofing the tops of foundations, but so far no moisture effects

are evident, even in the untreated shallow foundations. In order to make this comparison, some of the weathering wall foundations were treated on top with asphalt while others were left unprotected. Certain sections of foundations were treated also, while other sections were left untreated. While the study thus far has shown no sign of capillary moisture coming up through a concrete foundation of a reasonably good mixture, the cost of a waterproofing coat of heavy asphalt or tar is slight and the practice is a good safety measure. This is especially true in case of poor drainage. In the case of a heavy building where a deep foundation of a rich mixture of concrete is used there would be no danger from capillary moisture and no need for waterproofing.

## Forms for Pise' Walls

Forms for rammed earth wall construction should not be made of material less than 1½ inches thick. Two-inch planed lumber is satisfactory. Since only one form of such dimensions as shown in Fig. 20 is necessary for making a complete building, the expense is not excessive. The form shown in Fig. 20 was still in use after 13 years of service and has been used for building walls equivalent to six or eight poultry houses. It is in good condition today. Those who have built forms for rammed earth work have found a ready rental for them.

Forms used at this Station are made of tongue and grooved plank, but it is not absolutely necessary. However, it is necessary that the planks be straight and not warped so that they will fit together and make a straight side wall for the form. It is also true that the forms will last longer and remain in better condition if tongue and grooved plank are used. Tongue and grooved plank can be secured from the lumber yard by ordering ahead of time or may be obtained from a sash and door factory. It is important that these side walls be straight and true or much trouble will be encountered when trying to level the forms so as to obtain a straight wall. As soon as the forms are finished they should be given a coat of linseed

oil to prevent the lumber from drying and warping. Furthermore, whenever the forms are not in use, particular care should be taken to see that they are standing or lying in such a way that they will not warp. That is, if they are left leaning against a wall the top part of the form should be touching the wall its entire length. If the forms are allowed to become warped, it is extremely difficult to level them onto a wall.

Linseed oil is a good oil to put on the forms immediately after they are made, and this may be followed by a coat of ordinary paint on the outside, if desired. Used crankcase oil that has been drained from a tractor is satisfactory for the inside if two or three coats are applied.

The outward thrust caused by ramming a wall is tremendous, making it necessary to use heavy stiffeners or struts on each side of the forms.<sup>17</sup> These removable struts should not be more than 30 inches apart and should be from 4x4 inch stock. Struts made from 3x4 inch stock were tried but were not strong enough to hold, so 4x4 inch pieces were used and gave good service.

<sup>16</sup>The type of foundation shown in Fig. 19 has proved entirely satisfactory. It has been used under three buildings, with walls up to 10 feet in height.

<sup>17</sup>See Figs. 20 and 21.

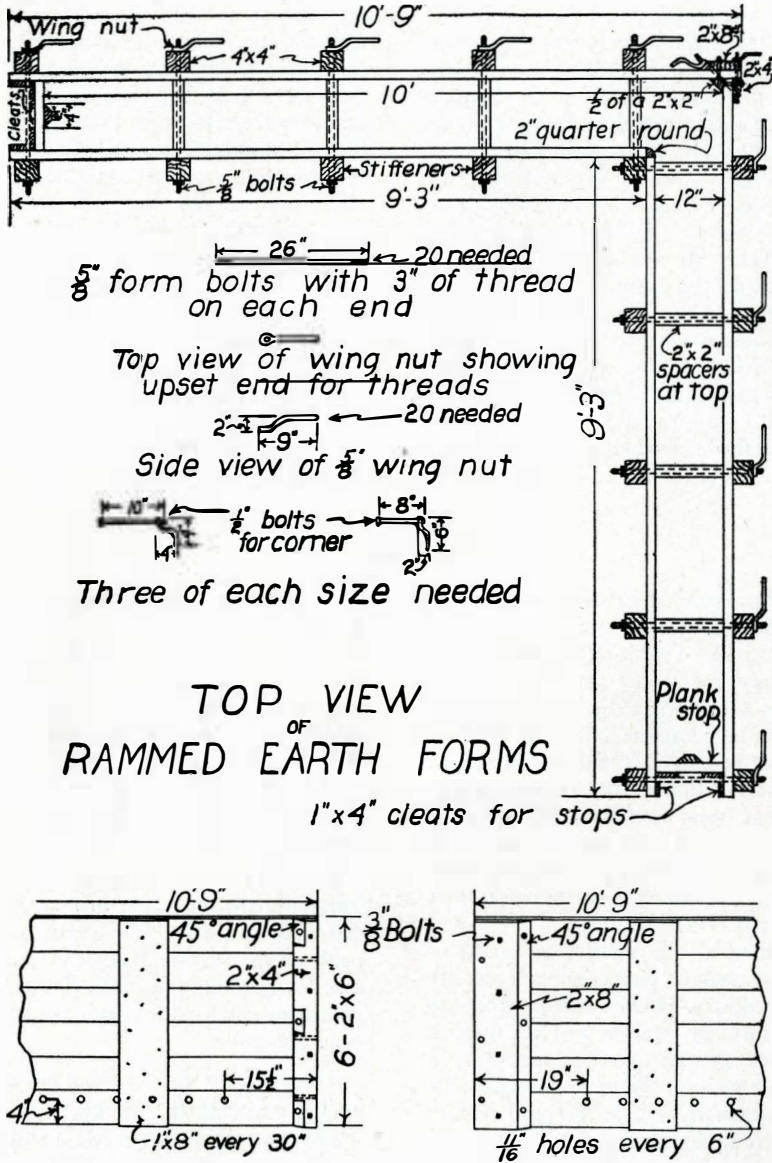
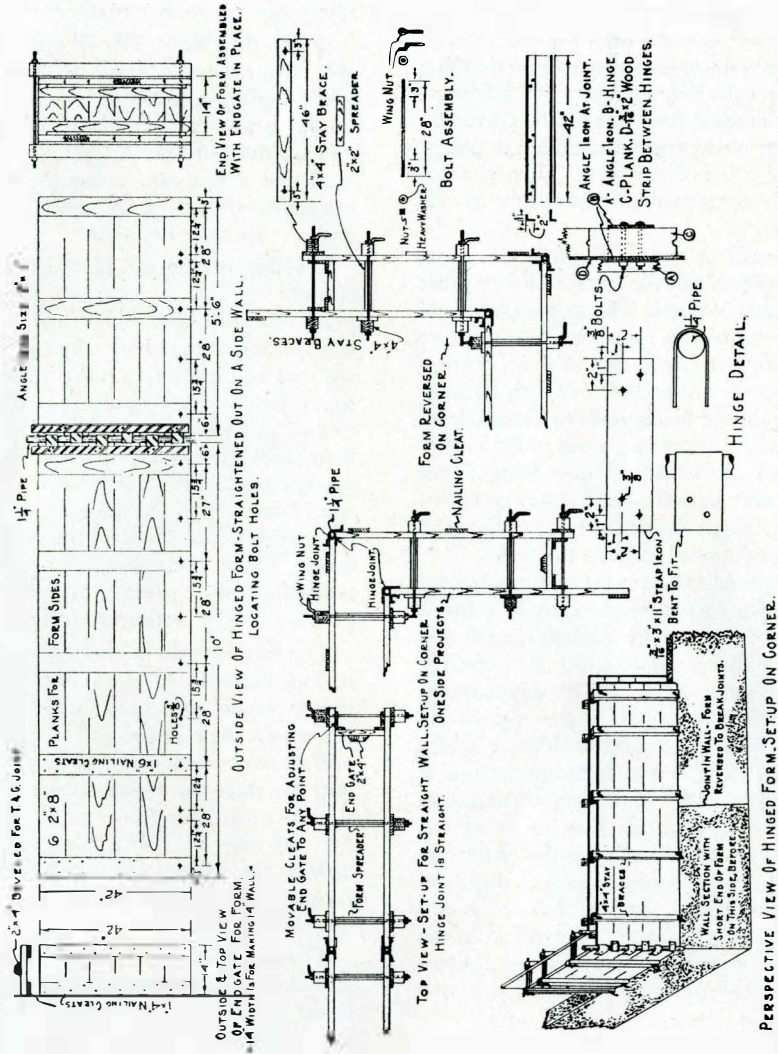


FIG. 20. PLAN FOR A LARGE FORM FOR RAMMED EARTH WALLS

A drawing of the large forms for rammed earth which were used in building the rammed earth poultry house, showing dimensions of the form for making a wall 12 inches thick. It also shows the dimensions of form bolts and wing nuts. The nailing cleats are not shown in the "top view."



**FIG. 21. A PLAN FOR A HINGED FORM FOR LARGE WALLS**

This form has a gas pipe hinge for building corners having any angle. Otherwise it is similar to the regular form shown in Fig. 20. The bolt lengths shown are for a 14-inch wall and can also be used for a thickness of 16 inches. For thicker walls longer bolts would be necessary. (Designed by H. DeLong.)



To insure making a straight wall it is necessary to use spacers between the outside and inside walls of the form as shown in Fig. 20. To prevent sharp corners on buildings, a 2 inch diagonal strip was placed on the inside corner of the form and nailed to one of the inside walls of the form. This makes a two inch bevel on the corners of all buildings.

The stops<sup>18</sup> or ends of the form are movable to any point in the form and they must also be made of plank. The stop is placed inside the end of the form or at window or door openings to form an end to the section of wall being rammed. A 2x4 inch strip tapered off should be fastened to the inside of the stop so as to form a groove in the end of the section and thus provide a better bond with the next section of wall. It is also necessary to nail cleats inside the form to hold the stops at any desired place in the form.

Some special means must be provided for fastening the corners on the outside walls of the form. A satisfactory method used at this Station is shown in Fig. 20. A 2x8 inch plank with one edge planed down to an angle of 45° was bolted to the end of one side wall. A 2x4 inch piece with three notches cut at 45° angles was bolted to the end of the other side wall. This arrangement allows for three bolts to cross the corner of the form and for three bolts parallel with one side. This design is very similar to other designs but is slightly simpler than some others. It also allows a small adjustment at the corner when leveling the forms by tightening or loosening the bolts extending across the corner.

The over-all length of the form is almost eleven feet. If it is desired to make a building in which inside dimensions are less than the length of the inside wall of the form, it will be necessary to shorten the form. However, regardless of the length, it will be nec-

essary to use two inch material for the sides.

**Oiling the Forms.** The oil on the inside of the form seems to work off into the dirt while ramming, making it necessary to re-oil the inside. Used crankcase oil is satisfactory for this purpose. A light covering of oil is all that is necessary unless the soil used is unusually wet. Wet soil will stick to the forms more than dry soils.

**Leveling the Forms.** In order to secure a straight wall it is necessary to level and plumb the side walls each time the form is set up. Sometimes both sides of the form will not be plumb or parallel to each other, so it is best to clamp the form to the foundation or preceding section of rammed earth, then level the outside form wall using the spacers to locate the inside wall. The bottom form bolts rest on the foundation or preceding section of wall to hold the weight of the form. These bolts may be removed by pounding them, using a ½ inch rod for a punch after the section is finished.

The form should be set in place as shown in Fig. 22, with the form bolts loose. The struts, spacers, and stops should be in place. Then by using a carpenter's level, plumb the outside wall on each side of the corner. This may be done by either lifting the corner slightly or by lifting one end or the other as the case may be. When the corner is level, tighten the bottom form bolts next to the corner. Also tighten the upper bolts with spacers in place.

Then take the level to each end in turn and plumb up the end and clamp it solidly to the wall. After the corner and both ends are plumb, the form bolts along each side may be tightened. Care must be taken not to put any severe side thrust onto the form until after two or three layers are rammed in the bottom to help hold it in place.

<sup>18</sup>See Fig. 20.

## **Building a Rammed Earth Poultry House**

This poultry house was built in farm size, being 16 feet wide by 32 feet long and having 12 inch walls all around. The house faced the south and was built after the plan

(No. 311) of the "South Dakota Poultry House," having a two-thirds pitch or combination roof and a straw loft. A few slight changes were made in plan 311 for the

rammed earth walls. The south side wall was made seven feet high and the north wall five feet, and the baffle-board shutter ventilators shown in the south side wall of plan 311 were made to fit into the window open-

ing by raising the lower sash. This eliminated the extra openings in the south side wall that would otherwise have been required. Since the top of the foundation must necessarily be the width of the wall, the founda-



**FIG. 22. RAMMED EARTH WALL FORMS LEVELED AND CLAMPED TO THE CONCRETE FOUNDATION**

A. The outside of the form showing the heavy 4x4 inch struts, also the form bolts and wing nuts which hold the struts against the form. Handles as shown on the forms are very convenient when handling and resetting.

B. The inside of the form showing the 1x8 inch boards which are fastened to the form with screws. These cleats hold the sections together after the form bolts and struts are removed. At the right the wall-stop is shown just back of the form bolts. Temporary cleats are nailed to the inside of the form on this side of the wall stop or "end gate" to prevent its pushing out.



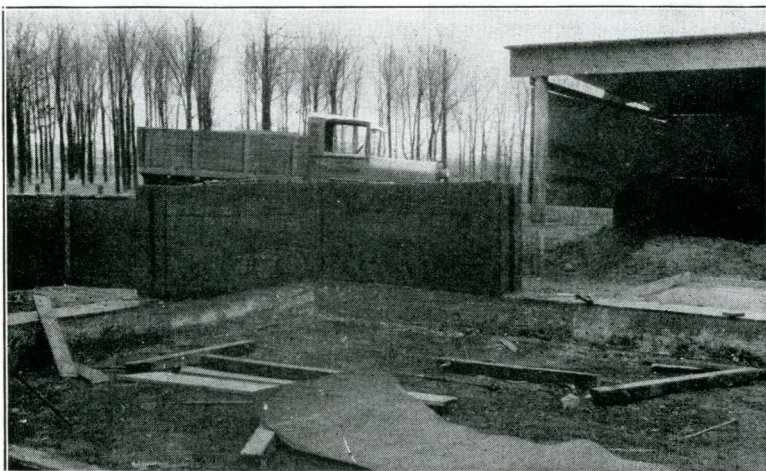


FIG. 23. A LARGE CORNER SECTION COMPLETED

This shows the first completed corner section of a rammed earth wall in process of construction. The end groove is shown at each end of the section. When the adjacent sections are built these grooves will be filled and thus make a weather proof joint. At the right background is the shelter for protecting the soil from rains.

tion was spread at the top and bottom, and a saving in concrete was made.<sup>19</sup> A concrete mixture of 1:2½:5 was used and the eight inch foundation was lightly reinforced with three-eighths inch steel rods at the top and bottom as a safety measure.

The house was built in the spring of 1932, between April 15 and June 6. The building of the walls, window and door frames, and the fitting of the plates was done by student labor at intermittent intervals (most of the work was done on week-ends), and practical methods such as would be used in actual construction were followed.

**The Soil Used.** Three kinds of soil were used in the walls: The black top soil that came out of the foundation trench; a yellow clay loam soil similar to Experimental Soil No. 2, taken from a basement excavation in the city; and a third, yellow clay loam with slightly more sand in it. The soils were piled in the shelter so that they could be readily mixed on the mixing board, and they were mixed in the proportion that would afford a satisfactory moisture content, as some of them were drier than others. The mixing of these three soils was done by counting the shovels of soil from each pile. No labora-

tory tests were made of the materials or of the moisture in the soil since it was desirable that the construction work be done under practical conditions. The proper moisture in the soil was judged by the hand and by the way it worked under the rammer. In judging the moisture a handful of the soil was squeezed together and dropped on a hard floor. It should stick together and mold in the hand but when dropped on the floor it should break apart in small pieces when the moisture is right. If it is too wet it will not ram down into a hard mass. A general idea of the amount of sand in each kind of soil being mixed was found by the practical test described heretofore, and the total sand in the final mixture probably averaged close to 45 per cent. This was not the optimum amount of sand. In fact it was rather low, and, as expected, the shrinkage joints were wider than had been experienced in the other large walls where the soil used contained a larger amount of sand. The shrinkage joints were very easily filled later, with cement mortar.

<sup>19</sup>Three additional buildings of rammed earth have now been built. In addition, more than 1000 feet of wall for experimental panels has been built.



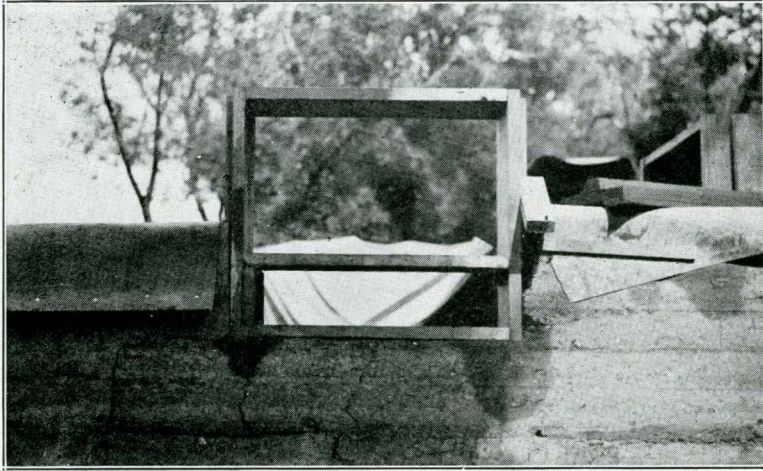


FIG. 24. SHOWING THE SETTING OF A SMALL WINDOW FRAME

This picture shows the window frame set in place as the *pisé* wall is rammed around it. The frame is of 2x12 inch material and the 2x3 inch strips are shown nailed onto the sides next to the wall. An earth wall was then rammed around these strips to make the joint wind proof. A heavy temporary brace of 2-inch material is shown set inside the window frame about eight inches from the bottom. This brace is very necessary and was raised when the sections above were built. When the soil is rammed above the frame vertical braces are installed in a similar way.

**Building the Wall.** Two forms were used on these walls part of the time, since they were available, although one large form is sufficient for a crew of three or even four men to work. The forms were first set up at the corners and rammed as full as desired. They were then straightened out, moved along the foundation and set up for a second section of wall and continued around the foundation at this height.

It is very important to keep the forms level and plumb at all times and to finish the top of the section as level as possible as the lower bolts of the form rest on the top of the wall in placing them for the next course above.

**Filling the Forms.** The forms were first painted on the inside with a coat of used crankcase oil as already described. About four inches of loose soil was then shoveled into them and leveled off, after which it was rammed until perfectly solid, and the process repeated. If the soil does not ram until perfectly hard, the moisture is not quite right. It is probably too wet. The soil was

mixed on the board, moved in a wheelbarrow and shoveled into the forms by one man, while two or three other men did the tamping. Care was used to have the soil mixed sufficiently to get the moisture content uniform throughout. The window frames, door frame and lower plate were all made from 2x12 inch plank, making them almost as wide as the wall. This was done for the added protection but it costs quite a little more than 2x8 inch material. The 2x8 inch material could be used in all places except for the door frames. One other advantage in using the 2x12 inch frames, however, is that the walls were rammed with the window frames in place, thereby getting a tighter fit. The frame was used for the end of the form and the earth rammed right up against it. A 2x3 inch strip was first nailed on to the outside of the window frame, so that this would make a weatherproof joint around the frame when the soil was rammed around it. This three inch strip should be tapered to two inches at the outer edge so that the shrinking force will not pull it away

from the frame to which it is nailed. The shrinking of the wall in some cases left open joints of one-fourth to one-half inch. These were filled and pointed up with mortar. The mortar was mixed 1 to 4 (1 part of cement to 4 parts of fine sand) and was mixed very dry so it would not shrink.

In ramming the soil over the window and door frames an extra plank extending one foot into the wall at each end was used for a lintel.<sup>20</sup> The reinforcing study indicates that reinforced concrete lintels would be more satisfactory for reinforcing here, and that the practice would be a good one for wide openings. In ramming over door and window frames it is necessary to set vertical false posts or planks into the frame opening until the wall above is entirely finished. After the wall is finished, ordinary window frames were set into this rough frame for the 12-light, 10x12 inch pane, double hung windows. As the top course of wall was being built, long anchor bolts were embedded for bolting down the plate. These bolts were five-eighths inch bolts 15 inches long with a large flat anchor washer two inches wide by six inches long and one-fourth inch thick. The anchor washer was, of course, embedded at the bolt head at a depth of 12 inches in the rammed earth, leaving two or three inches of the threaded end extending through the wall for securing the 2x12 inch plate on top. Anchoring the plate is very important in rammed earth construction and extra large round washers were used under the nut on top of the plate for this reason. The plate was of double two inch thickness. The under plate was 2x12 inches and the top plate was 2x4 inches. The under plate only was bolted down and the 2x4 inch top plate placed at the outside was securely nailed to it. The top of the wall was leveled with a thick layer of Portland cement mortar under the first plate. The roof, concrete floor, straw loft and inside equipment were put in as for any frame house. The inside earth wall was plastered where the birds were able to reach it. Pure Portland cement plaster in the proportion of one part of cement to three of sand was used.<sup>21</sup> Two places were left unplastered to see how badly the birds might

attack it, and as expected they worked on it in two or three places sufficiently to justify the recommendation for the practice of plastering. At one point a small hole has been picked in the wall to a depth of more than two inches. The band of plaster extended 30 inches above the floor and at the ends and back of the roosting alcove. Straight edge strips were tacked around the wall at the desired height for a gauge and a plasterer did the entire work in less than three hours' time. The wall was lightly wet down with a spray of water just before plastering. In constructing the gable ends it was not considered safe to ram the wall on a slant or with the pitch of the roof, because with hard ramming the soil breaks down to the lower level. The end was therefore rammed in horizontal sections, leaving a notched effect<sup>22</sup> and these notches were filled with concrete as the roof was framed. For poultry house construction the notches might be made larger, thereby requiring fewer settings of the form. The author urges the use of rammed earth or of rammed earth blocks for the gable end of the buildings. If frame construction is used it will have a much shorter life than the rest of the wall.

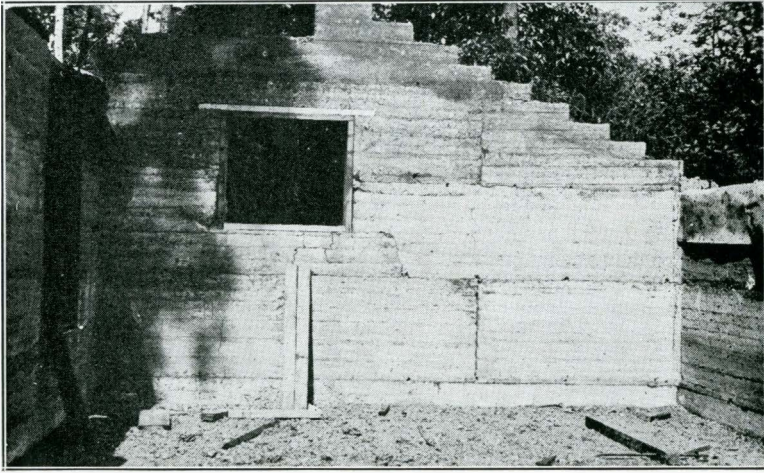
**Protecting the Walls During Construction.** During construction the tops of the earth walls were carefully protected against rain. During the night and when work was not in progress they were kept covered with a material that would turn the water and prevent its flowing down the surface. Strips of two-ply roofing were used and made excellent material for this purpose. Sisalkraft paper is also very satisfactory for this purpose and is cheaper. The strips were of such lengths that they could be handled by two men, and a light piece of lumber tacked along each edge of the strip helped hold it in place against the wind. When work was delayed so long that the lower section had become dry, the top of the wall was sprinkled

<sup>20</sup>See Fig. 25.

<sup>21</sup>This plaster should have contained one-fourth part of cement and  $3\frac{1}{2}$  parts of sand to 1 part of Portland cement. It should have been put on in two coats and the first coat should be nailed to the wall with 10d nails immediately after applying. The second coat should follow in a day or two.

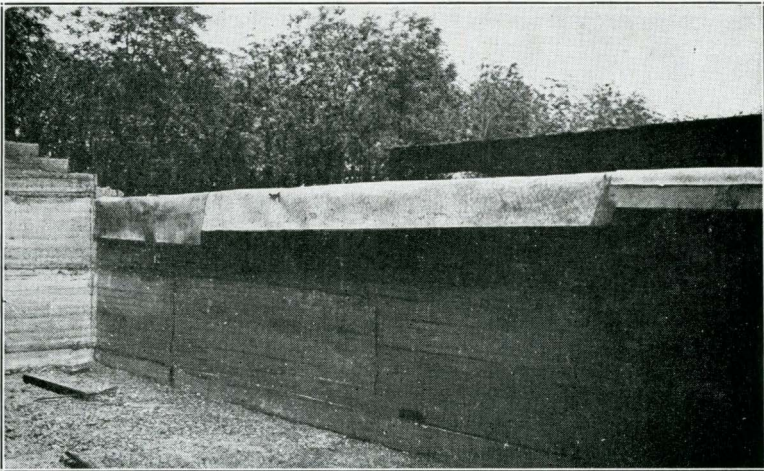
<sup>22</sup>See Fig. 25.





**FIG. 25. THE FINISHED WALLS OF THE RAMMED EARTH POULTRY HOUSE**

This is an inside view of the poultry house walls, showing one end. Since the gable end of the walls cannot be rammed very satisfactorily on the slant, or with the pitch of the roof, the end wall was notched as shown. The notches were filled with concrete between the frieze board and a form board placed inside as the roof was framed. The 2x12 inch plank over the heavy window frame was satisfactory as a lintel for a light wall. The opening at the peak above the window is for a small shutter ventilator.



**FIG. 26. PROTECTING THE TOP OF RAMMED EARTH WALLS DURING CONSTRUCTION**

The tops of rammed earth walls must be protected from rain at all times while the work is not in progress. Rain falling on the top of a pise' wall tends to soften it and when the rain flows down the side of the wall deep grooves will be cut. Strips of prepared roofing, when available, make an excellent protection. Sisalkraft paper was also found very satisfactory. Light boards tacked along the edge of the strip hold it in place and protect it against the wind. This picture also shows the joints in the wall between the sections as they were built. At the lower center may be seen a wooden block embedded in the wall for a nailing tie. Few of these are needed.





**FIG. 27. PROTECTING THE TOP OF RAMMED EARTH WALLS DURING CONSTRUCTION**

Sisalraft paper or old strips of prepared roofing are good for the purpose. The lower edge should stand away from the wall. Note the 2x6-inch vertical braces set inside the plank window frame to reinforce it while the wall was being rammed above it.

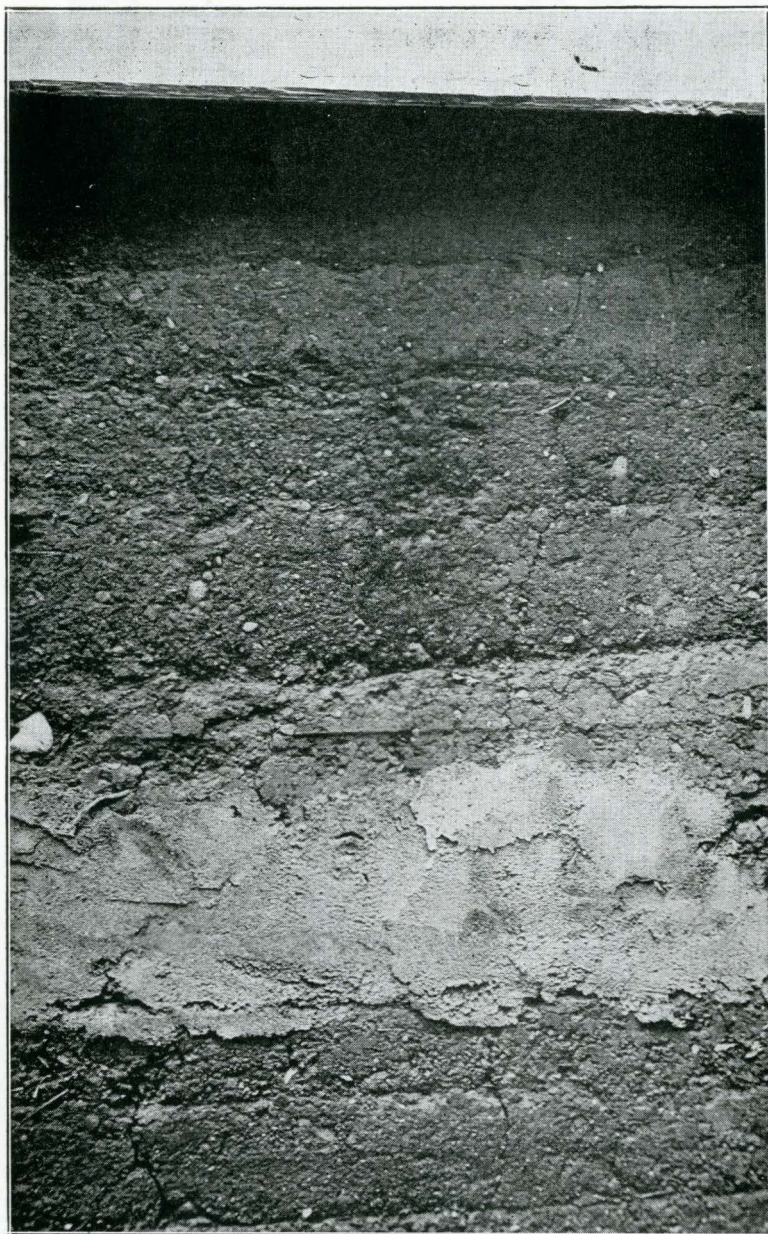
with water before starting to build the section above.

An experience in building this poultry house indicates the damage that can be expected from heavy rains when proper protection is not provided. On the day the roof was framed and the roof sheeting was being laid an exceptionally heavy downpour of rain came. The roof was in just the right stage of construction to carry the greater part of the water down to the wall but not over the eaves. This caused the water to flow down the wall surface at many points, where deep grooves were cut. The damage was the greatest around the window frames, where considerable repair was required.

**Repair and Retouching of the Walls.** The repair of damaged places in the wall was easily and quickly made. In repairing the deep grooves in the wall a few 8d nails were first driven in the bottom of the grooves, not closer than two or three inches, leaving the heads of the nails protrude one-half inch. The cavity was then filled with very dry ce-

ment mortar which remained entirely firm. As the walls shrink (and the amount of shrinkage will depend upon the amount of sand in the soil used) the joints in the wall will open slightly. These joints were easily and quickly filled with cement mortar. After the forms were removed the bolt holes through the wall were left. These bolt holes were filled by tamping them full of the same cement mortar. A small V-shaped trough about eight inches long and three inches high was used for feeding the mortar into the holes as the tamping was done with a round wooden rod.

The eaves of the rammed earth house are no wider than ordinarily used, having a horizontal projection of 12 inches. The walls are standing perfectly after 13 years. A blueprint plan, No. 312, for this rammed earth poultry house is available. More complete instructions for building a rammed earth poultry house, including stuccoing, are given in South Dakota Extension Circular No. 362.



**FIG. 28. REPAIRING HOLES IN A RAMMED EARTH WALL**

Repairing holes or other defects in a rammed earth wall is easily and quickly done with Portland cement mortar. Such a repair is shown in the above picture. The mortar is made by mixing one part of cement with four parts of sand and making a rather stiff dry mortar. The surface should be moist before applying the mortar. An extra safety measure is to drive a few old nails in the bottom of the hole to be repaired, leaving the heads stick up about one-half inch.





**FIG. 29. THE SOUTH DAKOTA POULTRY HOUSE BEFORE PAINTING THE WALLS**

The picture of this experimental house was taken just as it was finished and before it was covered. The spots in the walls that were injured by a heavy rain during construction, were easily and quickly repaired with Portland cement mortar. When the walls are left bare, outside window ledges should be provided with metal strips two inches wide extending below the ledge to force the water to drip from the edge instead of flowing down the face of the earth wall. Protection at the corners is most important. A picture of this house is shown on the cover.

### **Rammed Earth Blocks for Building Walls**

Rammed earth building blocks have been made and laid into walls in the same manner as for clay or cement building blocks. Rammed earth blocks are made from the same kind of soil as is used for building the monolithic or solid wall. The same test for quality of the soil is used. A sandy soil that is low in total clay colloids will be favorable. A heavy clay soil will be unfit to use and soils ranging in between these two will be medium in quality. As definitely reported in Experiment Station Bulletin No. 298, medium soils must be protected with a dependable covering.

**Size and Shape of the Blocks.** The first building blocks of rammed earth were made in 1933. Two small weathering walls were built of these blocks during the summer. In the winter of 1933-34 several hundred of the blocks were made and stored away. In the fall of 1935 a large section of wall (see Fig. 33), in an experimental building, was built

of blocks and since that time two inside walls have been built of them. The blocks were made 12 inches wide, by 18 inches long, by 6 inches deep. They weighed 80 pounds on the average. Half blocks were rammed for corners and openings. These blocks were laid flat in the wall, making a 12 inch thickness, and each block laid up approximately 120 square inches or seven-eighths of a foot of wall. They were found very heavy to handle in laying, and the size of the form has been changed to make these blocks 15½ inches long (16 inches with the mortar joint) and with the same width and depth. This length is the same as for most cement blocks that are made today. The blocks could be made in any desired size. The advantage in the larger block is that less mortar is required for laying them in the wall and the fewer mortar joints offer less opportunity for the infiltration of cold air. Thicker walls would be warmer in win-



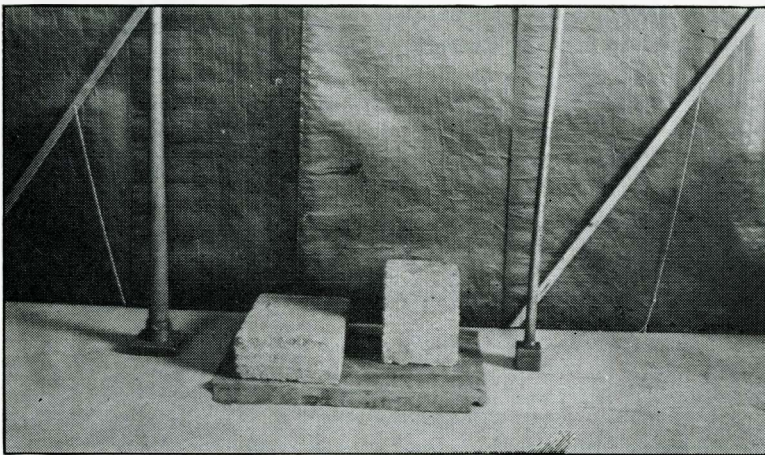
ter and cooler in summer and if thicker walls of this type were made, an 8 inch by 8 inch by 16½ inch block might be the best size to make and use in building a double wall. The blocks were rammed by hand. They were rammed in three layers and with the same rammers and intensity as for the monolithic wall. Mechanical rammers have been used and found exceedingly efficient in making blocks. Two special tools, working somewhat like ice tongs, were designed and used in lifting and handling blocks. Green blocks can be handled immediately after being removed from the form but they should be cured for 30 to 60 days before laying into the wall.

**Mortar Used for Laying up Wall of Rammed Earth Blocks.** The mortar used for laying up walls of these blocks was dagga plaster plus 10 per cent of Portland cement. A few years ago a report was made of some experimental work that was done by the Bureau of Agricultural Engineering in Washington, D. C. In this study varying amounts of Portland cement were added to soils for mortar and the effects of the admixture were

determined. As a result of these findings and knowing the physical characteristics of dagga plaster intimately, we concluded that a mixture of dagga plaster and 10 per cent by volume of Portland cement would make a good mortar. We tried it and it has proved so satisfactory we have used no other up to this time. It bonds with earth even better than common cement mortars and works nicely under the trowel. Its chief merit, of course, is its low cost.

The complete mixture for this mortar is: Two measures of plaster sand, one measure of sandy clay, and one-third measure of Portland cement. In mixing with shovels the following ratio is used: Six shovels of sand, three shovels of sandy clay, and one shovel of Portland cement.

This same mortar is being tested as a plaster covering for pise' walls and after nearly eight years' exposure is in almost perfect condition. Striking colors may be secured in this plaster from various colored clays. The sandy clay soil contained 46 per cent sand. A trial batch of the mortar is advised before



**FIG. 30. A FULL-SIZED BUILDING BLOCK OF PISE' AND A HALF-BLOCK OF THE SAME MATERIAL**

Earth walls made of building block will not be as durable or as weather proof as the solid walls. They are more convenient to use in building gables and inside partitions. Whole blocks of this size will weigh about 75 lbs. on the average after they have dried out. The common floor rammer on the left is sometimes used for going over the loose layer of soil in the form for the first time. It is used more in the wall forms than for building blocks. The rammer on the right is used for most of the ramming.



**FIG. 31. A FORM FOR MAKING BUILDING BLOCKS OF RAMMED EARTH**

This form has a heavy plank bottom and is lined throughout with light galvanized iron. The form is open and this side is dropped down for taking out the blocks. When a concrete floor is available the bottomless form shown in Fig. 32 is handier to use. The blocks in the background are test pieces and were not made in this form.

hand. If checks appear as it dries, more sand is needed.

**Forms for Making Rammed Earth Blocks.** Two different molds or forms were designed and built for making building blocks. Each form had a capacity of four full-sized blocks (see Figs. 31 and 32). One of these forms was made with a plank bottom while the other is bottomless and must be used on a solid concrete floor. The bottomless form was preferred by the workers.

Such forms must be heavily built and easily and quickly released for removing the blocks. They were lined with light galvanized iron, as shown in the plan. This eliminates the need for oiling the forms and works satisfactorily. Further improvement is needed in simplifying the bracing and in reducing the time required for releasing the finished blocks. With the present forms the speed of making blocks with two men working at a form is 3 blocks per man hour for hand work.

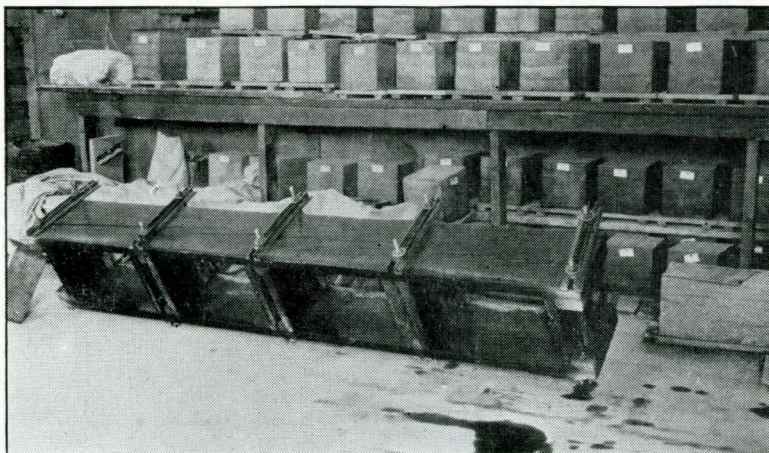
### **Walls of Block Compared to Monolithic Walls**

For rigid climates where a weather-proof wall is of importance, the monolithic wall has an advantage over the block wall. In durability the monolithic wall has also shown some advantage. Although the mortar described above has proved very much superior to the mud mortars used in adobe walls in the past, it will not last through a century or more of time, as is claimed for the monolithic walls of early history. The life of most walls of block or brick materials is limited to the life of the mortar joints. From

the standpoint of temperature control and for fire-proof qualities their advantages would be practically the same. For high walls or high gables the use of blocks has shown some advantage in construction speed.

For building low walls the construction speed will be considerably in favor of the monolithic rammed earth wall although no tests have been made to obtain accurate comparative figures. The building of the block





**FIG. 32. A FORM WITHOUT A BOTTOM FOR MAKING BUILDING BLOCKS**

This form is tipped up to show that it has no bottom. It is lighter and easier to handle. Only the ends are lined with metal in this form. A detailed plan for making a similar form is shown in Fig. 34. The blocks in the background are not building blocks.



**FIG. 33. A MACHINE SHED WITH RAMMED EARTH WALLS AND A SECTION OF WALL BUILT OF BLOCKS**

This building is 26 by 72 feet in size. It contains a section of wall built from blocks. The side and end not showing are covered with paint panels, many of them of transparent paints. This end is covered with dagga plaster and a few narrow panels of plaster are shown at the extreme rear. The roof truss for this building is designed to throw a fairly heavy roof thrust against the walls of the building. The building was two years old when the picture was taken. The gable end of frame construction is not good practice. It should be of a material as durable and as warm as the rest of the wall.



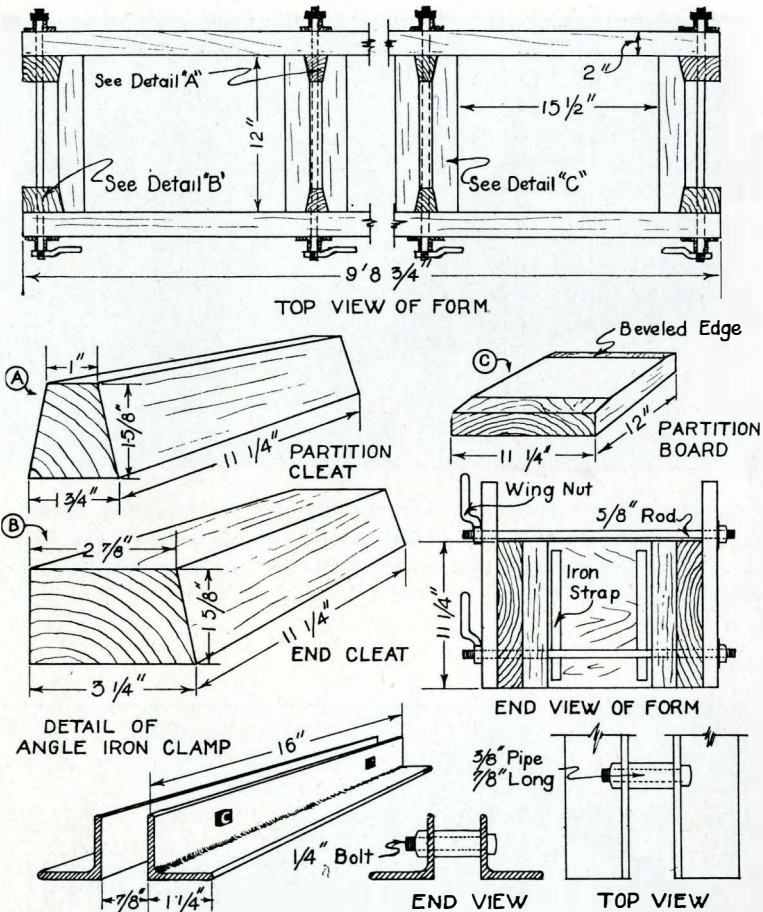


FIG. 34. PLANS FOR MAKING A FORM FOR BUILDING BLOCKS OF RAMMED EARTH

This form is 9 ft. 8 1/2 in. long over-all, and has a capacity of five whole blocks and one-half block. Half blocks will be used in about this ratio in building walls. The whole blocks will be 12 inches by 15 1/2 inches by 6 inches thick.

walls may seem more rapid because the work is divided into two periods of time, the making of the blocks, and the building of the wall. However, the material is handled several times more in building of blocks—the building of the monolithic wall

being a "once over, all over" process. The new form for making rammed earth blocks will be 9'-8 3/4" long and provides for making five whole blocks and one half block each time it is filled. A detailed plan for building this form is shown in Fig. 34.

## Thorough Distribution of Moisture Through the Soil Adds to the Quality of the Rammed Earth Wall

General observation in building of rammed earth indicates an advantage in using a soil that is uniformly moist throughout. When a soil has been allowed to become very dry under the shelter it is difficult to moisten it satisfactorily for immediate use. Experience indicates that a better quality wall will be secured if the moisture is thoroughly and uniformly distributed throughout the soil when it is rammed. Soil that is very dry will contain small hard clods even after it has been wet down and well

mixed. Perhaps the best way to avoid this situation is to wet down the pile of soil under the shelter occasionally or to wet down and mix the batch on the mixing board a week or more before it is to be used and pile it up. In this way the moisture will have time to spread through the pile before it is necessary to use it. The use of a tarpaulin for covering the soil aids in keeping it in good condition. The ideal way is to use it as it is freshly dug up.

## Comparison of a Puddled Earth or Mud with a Rammed Moist Earth—In Compressive Strength

In order to study the strength of earth as a building material, as it is affected by the manner of handling and placing it in the wall, a series of test pieces was made in the laboratory during the second week of September, 1937. Three base soils were used in

the study. These are described on page 10 and the sieve analysis for them is given in Table 1. No. 1 soil is a black clay soil containing very little sand. Soil No. 2 is a medium sandy clay soil; while soil No. 3 is a very sandy soil containing very little clay.



FIG. 35. PICTURES OF TEST PIECES OF "PUDDLED EARTH" AND "RAMMED MOIST" SERIES

One-third of the test pieces used in the strength study reported in Table 12 are shown in this picture. The cylindrical pieces are eight inches in diameter and were made in heights of 4, 6, and 9 inches. The steel mold used in making them and shown in the foreground is 8 by 16 inches. Test pieces are now made in this manner.

Two methods were compared: The one in which the soil was mixed with water to form a mud and with an admixture of straw, as earth is used in cob, chalk, and adobe construction; the other in which the soil is only moist and rammed into place as for pise' or rammed earth.

The test pieces were made in a cylindrical steel mold 8 inches in diameter by 16 inches high (see Fig. 35). The test pieces were made in three different depths. These depths were 4 inches, 6 inches and 9 inches, and for such slight variations in depth as unavoidably resulted in making them, corrections and the true strength are shown in Col. 10, Table 12. The principal reason for using test pieces of different depth was to try out this new mold for testing earth materials, and a secondary reason was for

checking the results of a former study. Four like pieces of each soil and for each depth and kind were made, making a total of 72 test pieces in all. The soil for the "puddled earth" pieces was taken from the same pile as for the "rammed moist" pieces. The earth was first thoroughly puddled and mixed with straw in a mortar box. It was then placed in the steel mold and rammed into place with the end of a 2 by 4 inch wood rammer. The moist earth was rammed in the same mold with an 18-pound steel hand rammer and care was used in ramming to see that the pieces were rammed with average intensity. The cylindrical hand rammer shown in Fig. 16 was used. The intention was to ram the test pieces with the average intensity that is used in building rammed earth walls. Earlier study has shown that the

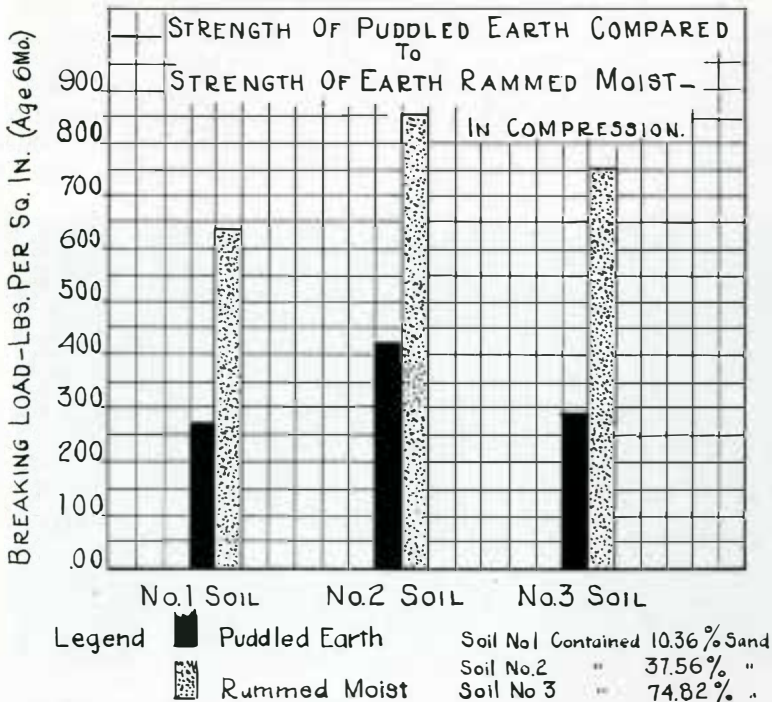


FIG. 36. PUDDLED EARTH WALLS DO NOT HAVE THE STRENGTH OF RAMMED MOIST WALLS

For all different types of soil and the different depths of test pieces the "puddled earth" showed a compressive strength only 43.2 per cent as great as the "rammed moist" pieces.



strength of rammed earth walls will vary materially with the intensity of ramming as reported in Table 6 of this bulletin. As each test piece was taken from the mold it was weighed and measured and placed on a shelf in the research laboratory, where the entire series was stored in a temperature of 65 to 70° F. until the time of testing. This period of time covered almost exactly six months. Straw was added to the puddled pieces at the rate of 122 pounds for each 1,000 pounds of earth. This is the amount recommended for adobe brick by Prof. H. C. Schwalen of the University of Arizona, who has done experimental work with this type of earth building material.

The straw was cut in lengths not to exceed six inches because of the relatively small test pieces. The age of these 72 test pieces was just six months when they were

broken. They were, of course, thoroughly air dried, containing from one per cent to two and one-half per cent of moisture when broken. The cylindrical test pieces with a diameter of 8 inches furnished a bearing surface of 50.27 square inches on top. Column 9 in Table 12 gives the ultimate strength of the cylindrical test piece of this cross-section and Column 10 shows the ultimate strength in pounds per square inch of bearing surface. The depth of the test pieces is shown in Column 11 and the decisive inverse ratio of strength to depth of test piece checks with the former work on this subject as recorded in Table 4, page 20. In that test which was made for the purpose of obtaining a correct coefficient for depth of test piece, the No. 3 base soil only was used. The comparison between the two studies must be made in "strength per square inch"

Table 12. A Comparison of Strength in Compression of Earth Building Material When Puddled as a Mud and When Rammed as a Moist Earth

1	2	3	4	5	6	7	8	9	10	11
Number of like pieces tested	Weight of pieces when made av. of 4	Weight of pieces when broken av. of 4	Loss of moisture in lbs. av. of 4	Loss of moisture in per cent av. of 4	Age when broken	Kind of soil (base soils)	Puddled mud or rammed moist	Ultimate strength in compression av. of 4	Strength in lbs. per sq. in. corrected for depth	Depth of pieces (approx.)
4	13.62 lbs.	11.36 lbs.	2.27	16.6%	6 mo.	No. 1	rammed	45,040 lbs.	896.	4. in.
4	16.44 lbs.	14.71 lbs.	1.73	10.5%	6 mo.	No. 2	rammed	50,768 lbs.	1015.	4. in.
4	16.06 lbs.	14.86 lbs.	1.20	7.5%	6 mo.	No. 3	rammed	50,785 lbs.	1010.	4. in.
						Av.	rammed	48,864 lbs.	973.7	4. in.
4	19.94 lbs.	16.85 lbs.	3.09	15.5%	6 mo.	No. 1	rammed	34,187 lbs.	676.	6. in.
4	24.12 lbs.	21.69 lbs.	2.52	10.4%	6 mo.	No. 2	rammed	47,180 lbs.	936.	6. in.
4	24.80 lbs.	22.73 lbs.	2.08	8.4%	6 mo.	No. 3	rammed	38,062 lbs.	757.	6. in.
						Av.	rammed	39,810 lbs.	790.	6. in.
4	30.00 lbs.	25.16 lbs.	4.83	16.1%	6 mo.	No. 1	rammed	18,000 lbs.	361.	9. in.
4	35.80 lbs.	32.06 lbs.	3.75	10.5%	6 mo.	No. 2	rammed	31,022 lbs.	617.	9. in.
4	37.40 lbs.	34.44 lbs.	2.94	7.8%	6 mo.	No. 3	rammed	25,077 lbs.	499.	9. in.
						Av.	rammed	24,699 lbs.	492.4	9. in.
4	13.25 lbs.	9.14 lbs.	4.11	31.0%	6 mo.	No. 1	puddled	17,012 lbs.	341.	4. in.
4	15.62 lbs.	12.48 lbs.	3.15	20.2%	6 mo.	No. 2	puddled	25,252 lbs.	519.	4. in.
4	16.25 lbs.	14.06 lbs.	2.19	13.5%	6 mo.	No. 3	puddled	18,380 lbs.	369.	4. in.
						Av.	puddled	20,215 lbs.	410.	4. in.
4	18.80 lbs.	13.37 lbs.	5.44	28.9%	6 mo.	No. 1	puddled	12,375 lbs.	243.	6. in.
4	22.37 lbs.	18.44 lbs.	3.93	13.2%	6 mo.	No. 2	puddled	21,255 lbs.	428.	6. in.
4	24.50 lbs.	20.89 lbs.	3.61	14.7%	6 mo.	No. 3	puddled	14,100 lbs.	280.	6. in.
						Av.	puddled	15,910 lbs.	317.	6. in.
4	28.75 lbs.	20.50 lbs.	8.27	28.7%	6 mo.	No. 1	puddled	11,710 lbs.	233.	9. in.
4	33.12 lbs.	27.84 lbs.	5.28	15.9%	6 mo.	No. 2	puddled	15,450 lbs.	307.	9. in.
4	34.81 lbs.	30.28 lbs.	4.53	13.0%	6 mo.	No. 3	puddled	10,657 lbs.	204.	9. in.
						Av.	puddled	12,606 lbs.	248.	9. in.

for the two tables, since the test pieces were of different size and shape. Another factor enters into the comparison also, due to the difference in age of the test pieces as given in each of the tables.

The results of this study show a decided advantage in the strength of earth material when rammed as a moist earth over the same earth material when puddled as mud. The compressive strength of all "puddled earth" test pieces, including the three different types of soil and the different depths,

averaged only 43.2 per cent as great as the "rammed moist" pieces. An interesting ratio is shown between the loss of moisture in the "rammed moist" pieces and the "puddled earth" pieces, as compared to the strength of the two materials. The loss in strength of the puddled material is no doubt largely due to the honeycombed structure of the material after the moisture has left it. A similar loss in strength is found in a concrete structure that is made from a very wet or fluid mixture.

### **A Cinder Admixture Study**

A study is underway to determine the effect of adding soft coal cinders to soils that are low in sand and somewhat high in clay colloids. As shown in Experiment Station Bulletin 298, the addition of sand to soils that are low in sand content improves the quality of the soil and the resistance of the rammed earth wall to weathering. Sandy soil also rams solid more quickly. A series of test pieces was made using base soils No. 1 and No. 2. Both of these soils are improved by an addition of sand. To these soils equal amounts of sand and cinders have been added to two series of test pieces which together with the check pieces will be broken at a late date. (See next column.) This is for comparing the effect of cinders and sand as an admixture, upon the strength and physical structure of the rammed earth pieces. To date two small weathering walls have been built using cinders as an admixture. In one of these walls one part of cinders by volume, to two parts of No. 2 base soil, was used. In the other wall one part of cinders was used to one part of the same soil. The walls were built for the purpose of comparing their weather resistance. We already have check walls of this soil in the yard which will be satisfactory for comparison.

Two conclusions have been drawn from the making of the test pieces. The cinders which contained a considerable amount of hard burned clinkers definitely increased the transverse strength of the material. A second conclusion was evident from ramming

the mixtures. The cinders caused the mixture to ram slightly quicker but not quite as solid as the sand admixture. The cinders used were from eastern mine-run coal burned under boilers in a power plant. A portion of the fine ash was screened out of the cinders used in this test, as the percentage of fine ash seemed to be higher than average. The sieve analysis of the cinders used showed 79.5 per cent retained on a one-fourth inch screen, 7.5 per cent retained on a one-eighth or No. 8 screen, 9.4 per cent was retained on a No. 50 screen, and 3.83 per cent passed through the No. 50 screen.

NOTE: Since the above report was made in the 1938 edition of this bulletin, final results have been secured on the cinder-admixture study as follows:

The cinders proved to be fully equal to sand in stabilizing rammed earth walls. They reduced both the shrinkage of the walls and the weathering action on them fully equal to admixtures of sand. The strength, in compression, was reduced by 10.8 per cent below that of the sand admixture but it is still much more than ample.

In the early years of study it was thought that the strength of rammed earth walls would be of paramount importance. This proved to be untrue. Resistance to weathering was found to be paramount. Any soil mixture with favorable resistance to weathering will have more than ample strength when rammed.

### A Few Brief Building Specifications

Sandy clay or sandy loam soils are most favorable of all soils for pise' or rammed earth walls. Heavy clay soils are unfit for use. Soils containing 18 to 24 per cent total clay colloids may be expected to stand for many years as a bare earth wall. Soils containing 24 to 39 per cent total clay colloids are medium soils. They will be perfectly satisfactory for rammed earth walls but will require a protective covering for the exterior surface. All of these soils will be improved by the addition of sand and many will be improved to a point where they will stand as bare earth walls. Builders should general-

ly plan on stuccoing earth walls, however.

The minimum thickness for any rammed earth wall should be 12 inches. The thickness should not be less than one and one-half inches for each foot of wall height. For dwelling houses the minimum thickness for the lower wall should be 18 inches, and 20 or 22 inches would be better. The extra thickness is recommended for insulating advantage rather than for strength.

Footings for the concrete foundation for earth walls should be ample for carrying a heavy load. They should vary in width from one and one-fourth to one and one-half

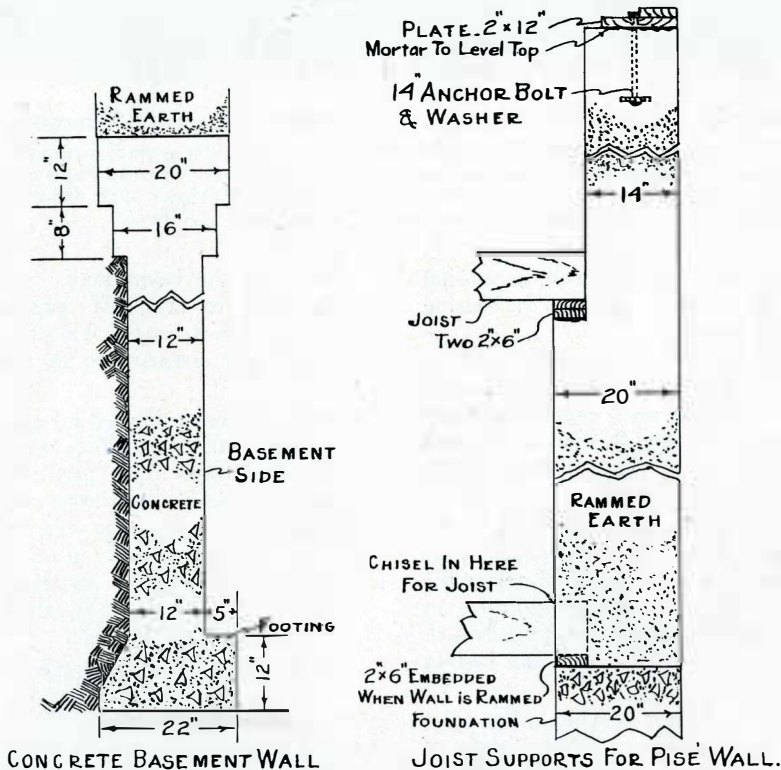
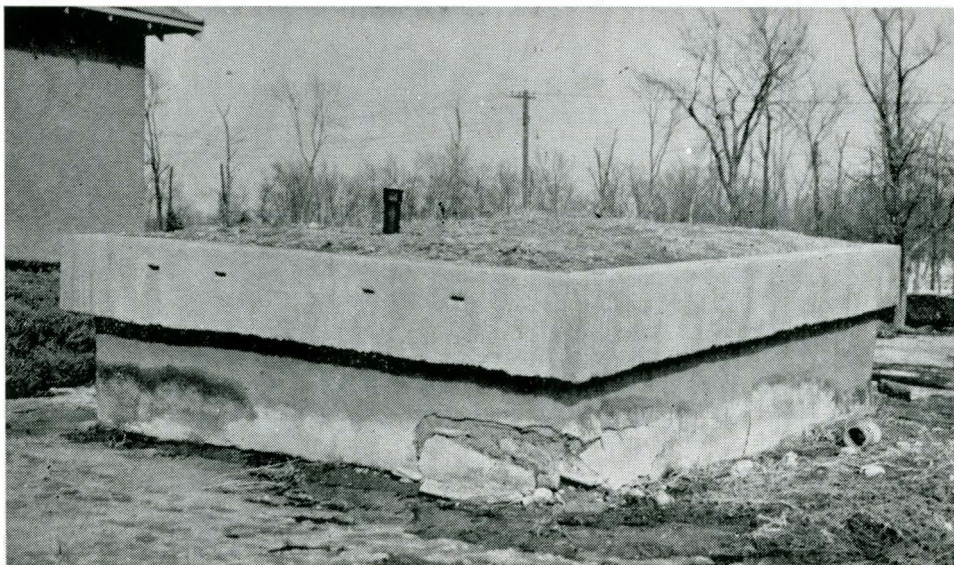


FIG. 37. A SUGGESTED FOOTING AND FOUNDATION PLAN FOR RAMMED EARTH WALLS

While the study is particularly concerned with poultry houses and livestock-building walls, a suggested plan for foundations and joist supports for dwelling house construction is shown above. House plans for brick or other masonry walls would be quite satisfactory for building of rammed earth.





**FIG. 38. A FAILURE OF RAMMED EARTH WALLS USED BELOW GROUND**

Rammed earth cannot be used below ground for building foundations. The rammed earth walls on the inside of this small experimental root cellar have caved and failed completely. Waterproofing used next to the soil on several panels helped only a very little. The walls were finished in October, 1938, and the walls failed completely in March, 1941. The exterior walls above ground were covered with stucco.

times the thickness of the wall, depending upon the height of the wall and the bearing strength of the soil.

The top of the foundation must be of the same width as the thickness of the wall. This full thickness must extend for a distance of one-half the thickness of the wall below the top, when the special type foundation is used.

Plank plates should be anchored to the earth wall by bolts that are embedded in the wall to a depth equal to the thickness of the wall at the plate. The bolt should carry an anchor washer or plate one-fourth inch thick and one square inch in area for each inch in thickness of the wall.

Sills or plates for carrying joists on a rammed earth wall may be of plank or of concrete. In no case should the ends of the joists rest directly on the earth wall. For normal floor loads the ledge for carrying the plate and joist ends should be not less than six inches (see Fig. 37).

"Pre-cast tile beam floors" lend themselves well to fire-proof construction in rammed earth structures. They may be used for flat roof construction as well as for floors.

Rammed earth blocks are practical for partition construction where fireproofing is important. Twelve-inch partitions will be satisfactory for dwelling house construction. Ordinary frame partition construction can be used very satisfactorily in rammed earth buildings. The great advantage of this material is in the outside walls, where its insulating value is most effective.

If thin walls are used it is not advisable to leave them unfinished and exposed to a hot drying sun for long periods. Too rapid drying of the side exposed to the sun may cause the wall to warp slightly. One long section of twelve-inch wall left standing throughout the summer was pulled out of line at the top by two or three inches in a length of 40 feet.



**FIG. 39. A SMALL DWELLING HOUSE BUILT WITH RAMMED EARTH WALLS IN PENNSYLVANIA**

This attractive little house was built by the Pennsylvania Housing and Town Planning Association of Philadelphia. Rammed earth construction lends itself to simple low walls with few window openings. Old Spanish architecture, which is popular in California, calls for a low, rambling, single-story house with few windows and a comparatively flat roof. Note the excellent proportions of this house. Window recesses on the outside add to the building and identify the earth wall. Special window ledge construction must be provided for carrying the water off the outer edge of the ledge.

If it is necessary to leave unfinished wall sections stand for more than three or four weeks in hot drying weather before installing the roof, some sort of shade or covering would be advisable.

The tops of unfinished walls must be protected against rain at all times during construction. Fig. 26 shows methods of tacking tough building paper over the top of the walls for this purpose. The lower edges of this paper must be held away from the wall to direct the flowing water away from the wall face.

When very dry soil is being used for building, the dry clods should be screened

out and the moisture should be added to the dry soil some time before it is used. This gives the moisture time to spread through the dry particles. The period of standing in the pile should not be less than overnight, and a longer period is better.

Good concrete foundations were necessary without exception for walls of rammed earth. They should extend 12 inches above ground. Shallow foundations were satisfactory under low poultry house walls when reinforced at top and bottom as shown in Fig. 19. All dwelling house foundations should extend below the frost line.

### **Summary and Comments**

Rammed earth or pise' walls are excellent in insulating quality, making an exceedingly warm wall in cold weather and a cool wall in hot summer. They should be made thick

for the greatest benefits, as their insulating quality increases directly with the thickness of the earth wall. In addition to being a good insulator, rammed earth walls are ex-





**FIG. 40. A MINNESOTA DWELLING HOUSE OF RAMMED EARTH**

This house was built near McGregor, Minnesota, by Mamie B. Nelson in 1938. Just the walls of the main house are built of rammed earth. The entry and porch are of frame construction. This is an example of a conventional roof used with pise' walls in an attractive setting of birch timber.

tremely stable. They are also fire proof, durable, and weather proof. Rammed earth is probably the most nearly weather proof of any wall material used today, having insulating qualities, and due to this fact, it lends itself well to modern air conditioning. However, the purpose of the Experiment Station in studying this material for wall construction was not for dwelling house construction but for the benefit of the poultryman and stockman. We are interested in the weather-proof properties of rammed earth walls rather than their low cost.

Rammed earth walls are not temporary in any sense. They are the most permanent of walls. They are somewhat tedious to build and when the wall is finished the rest of the building should be well built and tightly fitted so that the value of the insulated walls will not be lost. Perhaps the most valuable use of these walls is for the poultry house, the construction of which is outlined in Extension Circular 362. The poultry

house shown on the cover of this bulletin averaged, in a three-year temperature study, 5.9° F. warmer in early morning than a well-built frame house of the same size, dimensions and design. This was for the five coldest months of the year.

The speed of building the solid rammed earth wall will vary from 1½ to 2 cubic feet of wall per man hour depending upon the experience of the crew in planning the work and changing the forms. Mechanical rammers, driven by compressed air, rammed as high as 7 cubic feet per hour.

A sandy or comparatively light sandy soil is a favorable soil for building earth walls, and a heavy clay soil is unfit for use. An average or medium quality soil will not stand satisfactorily as a bare wall but must be protected with a covering of some material such as stucco.

It is the sand in the wall that resists the driving rains. Up to the present time no entirely dependable outside covering except



plasters has been proved, although ordinary good quality linseed oil paints have stood for five years on very sandy earth walls.

Screening the soil for rammed earth construction is necessary only when dry clods are found in it or when it contains undesirable trash. It is difficult to moisten the dry clods to their center for ramming and therefore best to screen them out.

Adding Portland cement to very sandy soils and especially fine sandy soils decidedly increased the strength. Adding cement to soils low in sand increased the strength very little, if any.

Adding hydrated lime to the soil reduced the strength materially and made the material crumbly. It did not reduce the resistance to weathering.

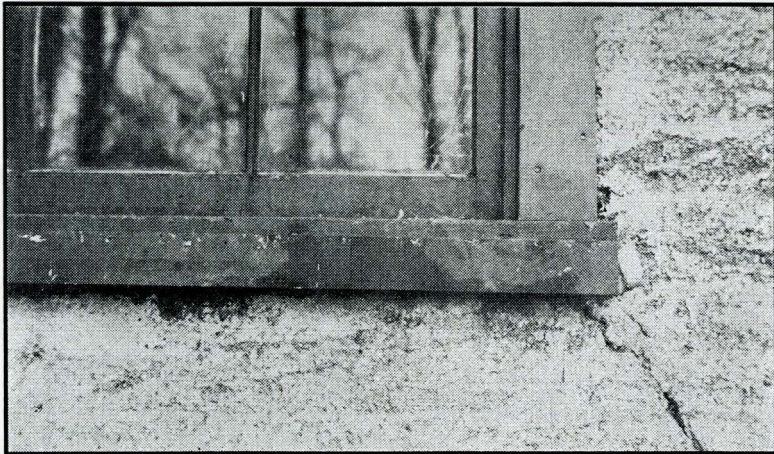
Window ledges should be made to direct the flow of water directly from their outer edge to the ground. Ordinary window ledges will carry the flow of water back underneath to the surface of the wall. The only trouble experienced with *piase'* walls from driving rains was at this point, where even the best walls were damaged.

Rammed earth block walls will not be as weather proof as the solid wall. Building with them may be more convenient for some who like to divide the building time into the two periods: making the blocks, and laying them in the wall. Building the solid wall is a "once over, all over" method and the total building time will be less for this type. Blocks are more convenient to use in high work such as the high gable ends of a building, and for partition walls.

An experienced crew will build a monolithic rammed earth wall in less time than is required for them to make adobe brick and then lay the brick into a wall.

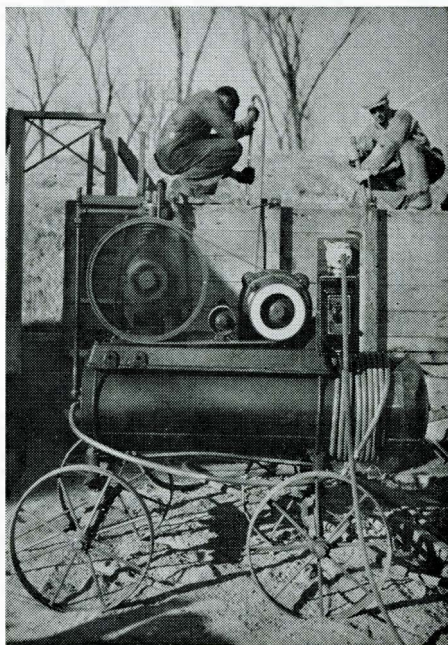
Hand rammers for building walls are readily made in the local welding shop. If made according to the suggestions, they will be durable and well balanced.

The mechanical air rammer was used for building the last large poultry house on the College Poultry Farm. It not only did satisfactory work but reduced the building time materially. Two air hammers could be used off the same large compressor and thus reduce the ramming time proportionately.



**FIG. 41. PROTECTION FOR AN OUTSIDE WINDOW LEDGE**

A close-up view of an outside window ledge in a rammed earth poultry house wall. Note the metal strip nailed around the edge to force the water from heavy rains to drop from the outer edge. Without the metal strip this water will run back under the ledge and flow down the face of the wall. Bare walls will suffer damage from this water.



**FIG. 42. AN AIR HAMMER AT WORK PACKING THE SOIL IN THE FORMS FOR A RAMMED EARTH WALL**

This is a small compressed air floor-rammer. The man at the left is working the air hammer. The air is conveyed to the air hammer through a large flexible hose which is shown. The flexible electric cord connecting the electric motor with the power line is shown in the foreground. The connection is seen just above the switch box on top of the compressed air tank. This compressor proved to be too small for the purpose. The compressor shown in Fig. 43 is the minimum size recommended for this work.

The only change made in the conventional air floor rammer was to have a square aluminum rammer head substituted for the cylindrical steel head. Either gas engine or electric power can be used to drive the compressor.

Earth walls are not recommended in locations where they would be inundated from flood water.

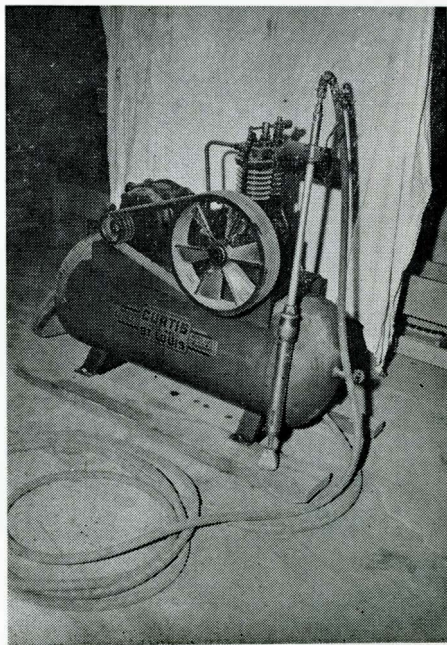
Coarse aggregate is of no advantage in rammed earth walls. It decreases the strength if too much is present. It also interferes with nailing of stucco wire.

Organic matter in ordinary top-soil will not injure the quality of earth walls except in cases where Portland cement is used as a stabilizer. Top-soil containing an unusual amount of organic matter should not be used.

**FIG. 43. AIR COMPRESSOR AND AIR HAMMER EQUIPMENT FOR RAMMING EARTH WALLS**

This mechanical rammer has been used in recent years of the work and has been found very satisfactory. It is conventional equipment except the square-faced aluminum rammer-head, which was substituted for the conventional head that came with the floor hammer. This equipment was purchased in 1936 at a cost of around \$500, including flexible cord for connecting up with electric power line and other miscellaneous items. The use of mechanical equipment speeds up the work of building rammed earth walls and reduces the cost materially.

The floor hammer and air hose cost \$110. The air compressor, tank and motor rails cost \$218.83 and the secondhand, 2-horse electric motor cost \$85. The air compressor has a capacity of 16.3 cu. ft. of air per minute. This is the minimum size recommended for driving a single hammer.





### **A List of Reference Books and Literature on Pisé' Construction**

NOTE: Rather than to quote extensively earlier work that has been done on pisé' de terre construction, the authors wish to list the following references dealing with the subject. Single copies of the bulletins listed can usually be obtained free of charge, while the books can be obtained at a very reasonable cost.

Farmers' Bulletin No. 1500, "Rammed Earth Walls for Buildings," United States Department of Agriculture.

Bulletin No. 472, California Agricultural Experiment Station, Berkeley, California.

A book, "Cottage Building in Cob, Pisé, Chalk and Clay," by Clough Williams-Ellis. Distributed by Charles Scribners Sons, New York City.

A booklet, "Lower Cost Buildings," by E. W. Coffin and H. B. Humphrey, The Publicity Corporation, 22 Thames St., New York City. No longer available.

A booklet, "Modern Pisé' Buildings," by Karl J. Ellington, Port Angeles, Wash.

A booklet, "Special Report No. 5," Building Research Board, London, England. No longer available.